INCORPORATING STATION RELATED MAINTENANCE AND AGING OUTAGES IN COMPOSITE SYSTEM RELIABILITY EVALUATION

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By

Hua Yang

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ABSTRACT

A power system is normally composed of a large number of generators and transmission lines that are connected through switching stations and substations. The quality and availability of power supply to the customer is highly dependent on the performance of the station equipment. Research shows that station related outages can have considerable impact on the composite system reliability.

The individual station components, the station configurations and the terminal connection topologies are important factors in bulk system reliability evaluation. The major components in a station are circuit breakers, bus bars and transformers and these elements are periodically removed from service in order to conduct preventive maintenance. The removal of equipment for maintenance creates a change in the station configuration and a more vulnerable system. The failure of a related major component during a station preventive maintenance outage can result in a system disturbance and customer load loss. The bulk of the existing infrastructure of most electric power systems has been installed over the last 30 to 50 years. Aging failures of system components are a growing issue in modern electric power systems. Station related preventive maintenance outages and aging failures are important factors that affect the system reliability.

This thesis examines the reliability implications of station related outages, including maintenance outages and aging outages in basic station configurations using two practical test systems. Models and techniques are created to incorporate these outages in composite system reliability evaluation. The techniques presented and the quantitative analyses illustrated in this thesis provide valuable information for a wide range of system planning, design, reinforcement and maintenance applications, including design and modification of power stations and station maintenance planning.

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LIST OF ABBREVIATIONS AND SYMBOLS

ADLC	Average Duration of Load Curtailment
BECI	Bulk Power/Energy Curtailment Index
BPACI	Bulk Power-supply Average MW Curtailment Index
BPII	Bulk Power Interruption Index
CB	Circuit Breaker
CEA	Canadian Electricity Association
CIGRE	International Council on Large Electric Systems
DPLVC	Daily Peak Load Variation Curve
EDC	Expected Damage Cost
EDLC	Expected Duration of Load Curtailment
EDNS	Expected Demand Not Supplied
EENS	Expected Energy Not Supplied
ELC	Expected Load Curtailed
ENLC	Expected Number of Load Curtailments
FOR	Forced Outage Rate
f/yr	failures per year
G	Generator
HL	Hierarchical Levels
HL-I	Hierarchical Level-I
HL-II	Hierarchical Level-II
HL-III	Hierarchical Level-III
hr	hour
IEEE	Institute of Electrical and Electronic Engineers
IEEE-RTS	IEEE Reliability Test System
IEAR	Interrupted Energy Assessment Rate

kV	kilo-Volt
kW	kilo-Watt
kWh	kilo-Watt-hour
km	kilometer
MW	Mega-Watt
MWh	Mega-Watt-hour
MECORE	Monte Carlo Simulation and Enumeration Composite System Reliability Evaluation Program
MBECI	Modified Bulk Energy Curtailment Index
L	Transmission Line
LDC	Load Duration Curve
OPF	Optimal Power Flow
occ/yr	occurrences per year
PLC	Probability of Load Curtailment
p.u.	per unit
RBTS	Roy Billinton Test System
SI	Severity Index
U	Unavailability
yr	year
CB(A)	Active failure of a circuit breaker
CB(P)	Passive failure of a circuit breaker
CB(T)	Total failure of a circuit breaker
CB(M)	Maintenance outage of a circuit breaker
S	Station
λ	Failure rate (f/yr)
μ	Repair rate (occ/yr)
r	Repair time (hr)
λ''	Maintenance outage rate (f/yr)
μ''	Maintenance duration rate (occ/yr)
r''	Maintenance time (hr)
λ_{12}	Common failure rate (f/yr)

μ_{12}	Common repair rate (occ/yr)
λ_a	Circuit breaker active failure rate (f/yr)
λ_p	Circuit breaker passive failure rate (f/yr)
μ_{sw}	Circuit breaker switching rate (occ/yr)
s	Switching time (hr)
λ_{aai}	Circuit breaker active failure rate due to aging in the *i*th year (f/yr)
λ_{api}	Circuit breaker passive failure rate due to aging in the *i*th year (f/yr)
μ_{asw}	Circuit breaker switching rate due to aging in the *i*th year (occ/yr)
μ_a	Replacement rate (occ/yr)
λ_b	Bus bar failure rate (f/yr)
μ_b	Bus bar repair rate (occ/yr)
λ_{ai}	Bus bar failure rate due to aging in the *i*th year (f/yr)
λ_t	Transformer failure rate (f/yr)
μ_t	Transformer repair rate (occ/yr)
λ_{seti}	Total failure rate of Set *i* (f/yr)
U_{seti}	Total unavailability of Set *i* (hr/yr)
r_{seti}	Average repair time of Set *i* (hr)
λ_{pp}	Failure rate due to forced failures overlapping forced outages (f/yr)
λ_{ap}	Failure rate due to active failures overlapping forced outages (f/yr)
λ_{pm}	Failure rate due to forced failures overlapping maintenance outages (f/yr)
λ_{am}	Failure rate due to active failures overlapping maintenance outages (f/yr)
t_u	Component useful life (yr)
μ	Mean value for a normal distribution
σ	Standard deviation for a normal distribution
α	Scale factor for a Weibull distribution
β	Shape factor for a Weibull distribution
k	Component slope factor
$f(t)$	Failure density function
$\lambda(t)$	Hazard rate function
$Q(t)$	Cumulative failure distribution

Chapter 1

Introduction

1.1 Introduction

Electrical energy has been delivered to consumers since Thomas Edison publicly presented a complete system of commercial electric lighting and power through the Pearl Street station in New York on September 4, 1882 [1]. Electric power systems make it possible to transmit electricity from generation sources to customers, from one city to another and from one country to another. Electric power systems are probably the most complex and largest systems in the world. The basic function of a power system is to supply its customers with electrical energy as economically and reliably as possible [2, 3]. According to data from the North American Electric Reliability Council (NERC) and analyses by the Electric Power Research Institute (EPRI), power outages from 1984 to the present have affected approximately 700,000 customers annually [4]. The Northeast Blackout of August 14, 2003 brought clearly into focus the fact that electric power systems are not as reliable and secure as expected. Reliability of power supply is becoming increasingly important in our modern society and is generally taken for granted by the general public.

The reliability of an electric power system is directly related to the economic investment in the system. Reliability and economic constraints always conflict and affect managerial decision making. Power system reliability is usually expressed in terms of indices that reflect the system capability and the service provided to its customers. The reliability criteria and techniques first applied in practical power systems were based on empirical experience and were all deterministically based. Many of them are still in use today. These criteria, however, are inherently deterministic and cannot account for the probabilistic or stochastic nature of system behavior, customer demands or component failures [2]. The application of probabilistic techniques to reliability evaluation can consider the inherent stochastic nature of the power system, provide quantitative measures for power system reliability and thus complement the limitations of deterministic techniques [2, 3]. Power system reliability has been analyzed using probabilistic techniques since the first major group of papers was published in 1947 [5]. Research over the last sixty years has been aimed at trying to evaluate power system reliability with the increasing use of probabilistic methods [5-12]. A wide range of criteria and probabilistic techniques have been developed and many are currently applied in actual power systems. Probabilistic indices are being increasingly accepted by power utilities and regulatory bodies worldwide and many Canadian utilities utilize probabilistic methods [13]. These techniques can provide effective information in the decision-making process of system planning, design, and operation.

Some of the basics of power system reliability assessment are introduced in this chapter including a brief review on composite generation and transmission system reliability evaluation. This chapter also describes the research objectives and gives a brief description of the impacts of station related outages in composite system reliability evaluation. An outline of the thesis is presented in the last section of this chapter.

1.2 Basic Introduction to Power System Reliability Evaluation

Reliability in general is a measure of how well a system operates within its specifications. The reliability of a power system is the degree of performance of the system elements that result in electricity being delivered to customers within accepted standards and in the amount desired [14]. Power system reliability can be divided into the two basic aspects of adequacy and security as shown in Figure 1.1. Adequacy is the ability of the electric system to supply the demand and energy requirements of its consumers, taking into account the outages of system elements. Security is the ability of the system to withstand sudden disturbances arising within the system [2]. System adequacy is associated with system steady state conditions while system security is associated with dynamic and transient system conditions. The research described in this thesis is focused on adequacy evaluation.

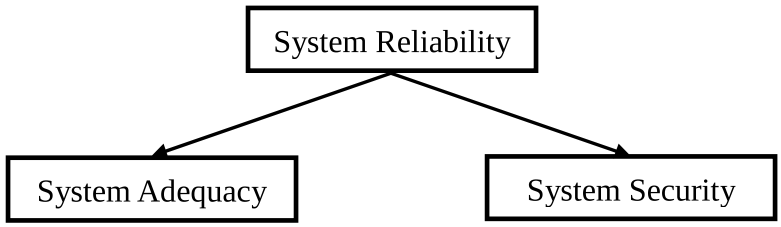

Figure 1.1: Subdivision of power system reliability

An electric power system is too large and complicated to analyze its reliability by treating it as a single entity. It is therefore divided into the three functional zones of generation, transmission and distribution shown in Figure 1.2. Each functional zone can be subdivided to analyze a subset of the zone. Particular subzones include individual generating stations, substations, flexible AC transmission systems (FACTS), high-voltage DC transmission (HVDC) and protection systems. The three functional zones can be organized into three hierarchical levels (HL) as shown in Figure 1.2. Hierarchical Level I (HL I) refers to only the generation facilities. Hierarchical Level II (HL II) refers to both the generation and transmission facilities and Hierarchical Level III (HL III) refers to all three functional zones.

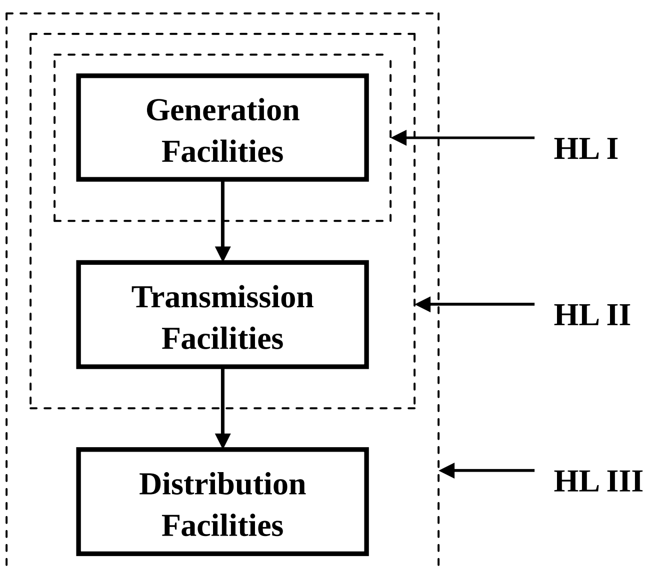

Figure 1.2: Basic functional zones and hierarchical levels

Reliability evaluation of power systems can be performed in each functional zone or at the three hierarchical levels. Reliability studies at HL I, are designated as generating capacity adequacy evaluation and are concerned with the adequacy of the total system generating capacity to meet the total system load demand. The application of probabilistic methods to HL I studies was first developed many years ago and has been extensively investigated [5-12]. HL II studies are designated as composite power system or bulk power system reliability assessment. Reliability evaluation of a composite system examines the ability of the system to deliver electrical energy to all the load points within accepted standards and in the amount desired. Considerable research has been done to develop applicable criteria and techniques in this area, and numerous books, technical reports and papers have been published [2, 3, 5-18]. HL III studies are not usually performed due to the scale and complexity of practical power systems. The reliability of the distribution system is usually analyzed separately and reliability indices obtained from an HL II assessment are used as input parameters to the analysis.

There are two fundamental methodologies applied in power system reliability evaluation. These approaches can be designated as analytical methods and Monte Carlo simulation. The analytical approach represents the system by mathematical models and evaluates the reliability indices from this model using direct numerical solutions. Monte Carlo simulation, on the other hand, estimates the reliability indices by simulating the actual process and random behavior of the system. The analytical approach can in certain cases provide accurate probabilistic indices in a comparatively short calculation time. The availability of high speed computers have made the Monte Carlo simulation approach more appealing since it can consider all aspects and contingencies in the power system process. Some of these effects are ignored to simplify the evaluation process when using the analytical approach. Monte Carlo simulation is described in detail in a later chapter. The analytical and simulation approaches can be combined to evaluate power system reliability in an effective and efficient manner.

1.3 Introduction to Composite System Reliability Studies

The research described in this thesis concentrates on HL II analysis. These studies involve assessing the ability of the composite generation and transmission system to not only satisfy the total system load demand but also tolerate random failures and perform preventive maintenance of electric equipment. Reliability performance of a composite system is normally determined using the reliability parameters and capacities of the generation and transmission facilities, the load demands and the system topology. The basic modeling approach in HL II analysis is shown in Figure 1.3. The generation and transmission model and the load model are combined to produce the system reliability indices. The generation and transmission model can be developed using analytical or Monte Carlo simulation approaches. The load model can be represented by the daily peak load variation curve (DPLVC) or the load duration curve (LDC). The DPLVC involves the peak loads of each day while the LDC uses the individual hourly loads in a given period.

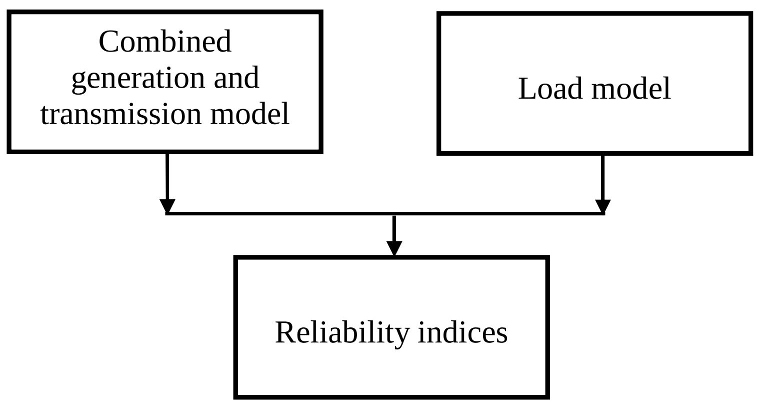

Fig. 1.3: Basic modeling approach for HL II analysis

Research done on composite system reliability can be categorized into the two aspects of adequacy assessment and security assessment as shown in Figure 1.1. There are far more publications concerning composite system adequacy assessment than security assessment. Many researchers have worked on the development of modeling and evaluation techniques using analytical and simulation approaches, and to create quantitative frameworks for HL II adequacy assessment in regulated and deregulated systems. Related technical issues in composite system reliability assessment include the effects of operational parameters, load uncertainty, voltage stability problems, power wheeling, weather, non-conventional energy sources, protection systems, flexible AC transmission systems (FACTS), high voltage DC transmission links (HVDC) and station originated multiple outages, etc. [10-12, 16]. The literature on composite system reliability assessment is not as extensive and intensive as that on generating capacity adequacy analysis but is beginning to receive increasing attention from researchers and practitioners.

The reliability criteria applied in a practical composite system can be defined as the set of conditions that should be satisfied in order to achieve the required reliability. Reliability is categorized by probabilistic indices obtained from adequacy evaluation of the system, and performance tests including deterministic criteria gained from empirical analysis [17]. Reliability indices are numerical parameters which provide quantitative measures of system and load point reliability. Performance criteria, however, are represented by a series of contingencies that the composite system should be able to withstand. These include load and dispatch conditions together with generation and transmission outages. Quantitative reliability indices are important parameters and can provide comprehensive information in power system planning, design and operation.

Composite system outages can be classified into four major categories: independent outages, dependent outages, common cause or common mode outages and station originated outages [2, 15]. Multiple independent outages are the easiest to evaluate and are referred to as overlapping outages. A system component is usually represented by a conventional two-state model containing the up and down states. Many of the evaluation techniques currently used in composite system reliability were developed under the assumption that all the component outages are independent. Dependent outages rely on the occurrence of one or more other outages and usually are not included in system reliability evaluation. A common cause outage results in an event consisting of two or more simultaneous outages due to the same external reason [19]. Common cause outages are incorporated in this research and are described in Chapter 2. Station originated outages are caused by the failure of one or more station components. The incorporation of these outages in composite system reliability studies is important as station related failures can cause the forced removal from service of two or more connected electric circuits.

This thesis focuses on composite system reliability evaluation incorporating station related outages. Stations are important elements in electric power systems and are used to connect power sources, transmission lines and customers. The term “stations” includes distribution stations, transmission substations and switching stations. Distribution stations are related to distribution system reliability while the other two station types are associated with composite system reliability. Substations and switching stations (herein referred to only as stations) are important parts of a composite power system. Failure events in stations often result in multiple outages of generators, lines, and bulk load points in a composite system and can have serious impacts on the system reliability and stability. Considerable research has been conducted to develop mathematical models and techniques for station reliability evaluation and to incorporate the effects of station originated failures in composite system reliability performance [20-28].

A station generally contains circuit breakers, bus bars and isolators and these elements are periodically removed from service in order to conduct preventive maintenance. As a result, a system component may be removed from service due to a station related maintenance outage, in addition to removal due to a forced outage. The bulk of the existing infrastructure of most electric power systems has been installed over the last 30 to 50 years [4]. From a reliability point of view, equipment aging involves an increased risk of failure. Aging failure of system components is a growing issue in modern electric power systems.

1.4 The Research Scope and Objectives

The objectives of this thesis are to develop models and techniques to incorporate station related outages, including maintenance outages and aging outages, in composite system reliability evaluation. This includes an investigation of the effects of these types of failure events on the reliability of the load points and the system and the sensitivity of the reliability to variations in component reliability parameters. The research examines the reliability implications of maintenance and aging failures in the basic station configurations using two practical test systems. The research can be categorized into three aspects: incorporating station related maintenance outages, sensitivity studies, and incorporating station related aging outages.

1.4.1 Incorporating Station Maintenance Outages in Composite System Reliability Evaluation

The purpose of maintenance is to increase the life time of the equipment and keep it in good working condition. In a practical power system, maintenance is a continuous activity and is an important part of what is usually called asset management. It is considered to be essential for ensuring high component and system reliability. There are two basic maintenance policies: scheduled maintenance and predictive maintenance [29]. Scheduled maintenance is carried out at regular intervals and is the most frequently used policy. Predictive maintenance, however, is carried out when it is deemed necessary, based on periodic inspections, diagnostic tests or other means of condition monitoring. The research in this thesis is mainly focused on scheduled maintenance of station components.

The major elements in a substation or a switching station are circuit breakers, bus bars and transformers. These elements are periodically removed from service to perform preventive maintenance. When a component maintenance outage is overlapped by another component forced outage, it can cause system failure and lower system reliability [30]. Station related maintenance outages are ignored in many studies. In order to examine the effects of station related maintenance outages, component reliability data such as mean times to failure, repair times, maintenance rates and maintenance durations are required. The objective of this research is to develop probabilistic models of station components including scheduled maintenance and to examine the effects of station related maintenance outages on composite system reliability.

1.4.2 Sensitivity Analysis

Previous studies show that substation and switching station related outages can have considerable effect on the reliability of a composite power system [20-28]. The reliability of a composite system is a function of the reliability of the individual station components and the station configurations. Individual component reliability is expressed by the failure rate, repair rate, maintenance outage rate and maintenance duration rate. The component failure rate is affected by a variety of factors, such as mechanical design, preventive maintenance practices and variations in the environment. The maintenance rate may also change due to adjustment of maintenance strategies. The individual component reliability varies over its life cycle due to variations in the component reliability parameters, such as the failure and maintenance rates. Sensitivity analysis is used to examine how variations in the station component reliability data affect the reliability indices of a composite system.

1.4.3 Incorporating Station Aging Failures in Composite System Reliability Evaluation

The failure characteristic of a power system component generally follows the well known bathtub curve. The failure rate increases rapidly when the component life reaches the wear-out period. When a component fails due to an aging failure, it cannot usually be repaired and must be restored or replaced. Aging failures of station components, such as transformers, circuit breakers and bus bars, are a major concern in composite power system planning and operation as more and more station components approach the wear-out phase.

Station related aging outages are not generally taken into consideration. Probabilistic models of station components involving aging failures and relevant evaluation techniques have been developed in order to examine the effects of station related aging outages. Two techniques are presented and compared: one is designated as the accurate method and the other is an approximate approach. The objective of this research is to investigate the effects of station related aging outages on composite system reliability evaluation and to examine the relative effects of variations due to component age.

1.5 Outline of the Thesis

There are seven chapters in this thesis. The first chapter provides a brief background on reliability evaluation of electric power systems and notes that station related maintenance and aging outages are important factors in station reliability. This chapter also presents the scope and objectives of the research described in this thesis.

Chapter 2 covers the theory of Monte Carlo simulation, the introduction of composite system reliability indices and a brief description of a computer software known as MECORE [31] used in the composite system reliability evaluation. The MECORE software is based on Monte Carlo simulation using the state sampling technique. The load point and system indices obtained using MECORE are described in this chapter. Two composite test systems known as the RBTS [32] and the IEEE-RTS [33] are used in this research and are briefly introduced in this chapter. Base case studies on the two test systems are presented and further reliability studies are conducted considering generation transformers, load point transformers and common mode failures.

Mathematical modeling and techniques to incorporate station maintenance outages in composite system reliability evaluation are described in Chapter 3. The main evaluation technique used in this thesis is the minimal cut set method. The minimal cut sets of the system define the failure modes of the system. A reliability framework can be deduced from the system operational logic and the system network diagram in terms of minimal cut sets. This method is illustrated using a ring bus station in the RBTS.

In Chapter 4, station related maintenance outages are incorporated in the reliability evaluation of two composite power systems, the RBTS and the IEEE-RTS. Four different kinds of station configurations are incorporated in the RBTS. They are ring bus, double bus double breaker, one and one half breaker and one and one third breaker configurations. The reliability of the IEEE-RTS with ring bus configurations is evaluated and some stations are modified to one and one half breaker configurations to improve the IEEE-RTS reliability. Base case studies are presented in this chapter for the RBTS and the modified RBTS with the four different station schemes and the IEEE-RTS with ring bus schemes and mixed ring bus and one and one half breaker schemes.

Chapter 5 contains a series of sensitivity studies on the two test systems. Reliability sensitivity studies are conducted for the modified RBTS with ring bus, double bus double breaker, one and one half breaker and one and one third breaker schemes. Similar studies are described for the IEEE-RTS with ring bus schemes and with mixed ring bus and one and one half breaker schemes.

Chapter 6 examines two different evaluation techniques to incorporate station component aging failures in composite system reliability evaluation. Two probability distributions, the normal distribution model and the Weibull distribution model, are used to calculate component unavailability due to aging failures. A second technique is proposed and used to examine the effect of aging failures of breakers and busbars on the reliability of the composite test systems.

Finally, Chapter 7 summarizes the research described in this thesis and presents the conclusions produced from this research.

Chapter 2

Composite System Reliability Evaluation

2.1 Introduction

The objective of composite generation and transmission system reliability analysis is to assess the ability of the system to meet the load requirements at the major load points. The impacts of both generating sources and transmission facilities are taken into consideration. HL II adequacy assessment is complicated since it includes aspects of system analysis and physical considerations. A series of system analyses are performed during the assessment process, such as load flow calculations, contingency analysis, generation rescheduling, circuit overload alleviation and load shedding, etc. Considerable research has been carried out to include related physical issues, such as the derated states of generating units, non-conventional energy sources, regional weather effects, load uncertainty, voltage stability problems, power wheeling, protection systems, flexible AC transmission systems (FACTS), high voltage DC transmission links (HVDC) and station originated multiple outages, etc. [10-12, 16]. This research is still incomplete and in progress.

As noted earlier, the reliability criteria applied in a practical composite system can be categorized as probabilistic indices obtained from adequacy evaluation of the system, and performance tests involving deterministic criteria gained from empirical analysis. Composite system probabilistic reliability indices can be divided into the two categories of predictive and past performance indices. Significant effort has been applied to develop techniques for both predicting and assessing the reliability performance of actual power systems [5-18]. Predictive indices are associated with adequacy assessment and provide estimates of future system reliability. Past performance indices, however, are overall system reliability measures that include operational impacts. Predictive indices are associated with system planning while past performance indices are related to actual operations. The research work performed in this thesis is focused on assessing system predictive indices.

Reliability indices can be used to predict the performance of different system designs, reinforcements and expansion plans and the related cost/worth of the alternatives. Two sets of indices, designated as load point and system indices are used to measure composite system reliability. The load point indices provide information on the individual load point reliabilities and the system weak points and also provide input values to reliability evaluations of connected distribution systems. The system indices can be produced by aggregating the individual load point indices and can be used to compare different alternatives in bulk power system planning and design. Both the load point and system indices are required in a complete evaluation of bulk system reliability. The evaluation technique can be either analytical enumeration or Monte Carlo simulation. Analytical techniques have been extensively developed for HL II studies [10-12, 16]. Monte Carlo simulation techniques have attracted considerable interest due to their flexibility in incorporating complex operating conditions and system considerations. The reliability studies in this thesis are based mainly on Monte Carlo simulation. This chapter provides a brief description of Monte Carlo simulation, an introduction to composite system reliability indices and an evaluation software. The concepts are illustrated by application to two composite test systems.

2.2 Monte Carlo Simulation

Monte Carlo simulation is a general designation for stochastic simulation using random numbers and is applied in many areas. In electric power systems, this method is used to estimate the reliability indices by simulating the actual process and random behavior of the system, such as the number of failures, the time between failures, the restoration times, etc. The method can calculate not only reliability indices in the form of expected or average values of the random variables, but also the distributions of these indices which analytical techniques generally cannot. Other system factors such as reservoir operating conditions, weather effects, etc. can also be simulated.

The simulation method relies on random number generation and solves the problem by a series of experiments in simulated time. Generation and conversion of random numbers are fundamental parts of Monte Carlo simulation. Random numbers are generated by a digital computer and their values are uniformly distributed between 0 and 1. The uniform random numbers are sometimes converted into other non-uniform distributions in the simulation process. Monte Carlo simulation can be divided into random (non-sequential) and sequential approaches. The random approaches include the state sampling and the state transition sampling techniques. In the non-sequential simulation method, the simulation process in each hour is considered to be independent of every other hour. In the sequential simulation, the equipment status is not independent of its status in adjacent hours and is created chronologically. As a result, sequential simulation can be used to calculate accurate time-related indices such as the frequency and duration. These simulation approaches are briefly described as the following.

State sampling approach

In the state sampling approach, each component state is randomly sampled and combined to form the total system state. The behavior of a component such as a generator, a transmission line, a transformer, etc. in a bulk system can be represented by a uniform distribution between [0, 1]. It is assumed that component failures are independent events and each component has two states involving failure and success. The state of the *i*th component is indicated by S_i and its failure probability is indicated by P_i. The total system state is expressed by the vector S, where $S = (S_1, \ldots, S_i, \ldots, S_n)$ and there are n components in the system. The state sampling approach can be summarized in the following steps:

Step 1. A uniform random number U_i is generated for the *i*th component.

Step 2. The component state is determined using this random number as follows.

$$S_i = \begin{cases} 0 \quad (successs \quad state) & if \quad U_i \geq P_i \\ 1 \quad (failure \quad state) & if \quad 0 \leq U_i < P_i \end{cases} \tag{2.1}$$

Step 3. The system state is obtained by combining all the component states determined in Step 2.

Step 4. If the system state S is zero, the system is in the normal operating state and

Steps 1-4 are repeated; otherwise the system is in a contingency state and goes to Step 5.

Step 5. When a contingency state occurs, linear programming optimization can be used to reschedule generation, relieve transmission line overload and minimize the total load curtailment.

Step 6. Reliability indices for each load point and system are accumulated. Steps 1-5 are repeated for the desired number of simulations or the stopping criterion is satisfied.

Using this method, the frequency of failure is estimated approximately using the number of failures encountered during the simulation process.

State transition sampling approach

The state transition sampling approach focuses on state transition of the whole system rather than on component states or state durations. This approach only applies to exponentially distributed component state durations. The approach used in composite system reliability evaluation is described in the following steps.

Step 1. All the components in the bulk system are first considered to be in the up state and thus the system is in the normal operating state.

Step 2. The state transition of any component may cause a system state transition. A uniform distributed random number is generated to determine the next system state transition.

Step 3. If the system state is a contingency state when at least one component fails, the minimization model [3] of load curtailment is used to assess the adequacy of this system state. Otherwise, the process goes to the next step.

Step 4. Steps 1-3 are repeated for the desired number of simulations or until the stopping criterion is satisfied.

This method can be used to calculate the actual frequency index since it evaluates the system indices based on system transitions. This technique is usually slower than the state sampling simulation approach.

State duration sampling approach

The state duration sampling approach is grounded on sampling the probability distributions of the component state durations. The chronological component state transition processes are simulated for all the components and these processes are combined to create the chronological system state transition process. Any distribution function can be used in the state duration sampling approach. For two-state components, the operating and repair states are assumed to be exponential distributed. The approach used in composite system reliability evaluation is presented in the following steps.

Step 1. The initial state of each component is specified, and is usually assumed to be the up state.

Step 2. A uniform distributed random number U_i is generated to determine the state duration of each component. Based on an exponential distribution, the state duration is

$$T_i = -\frac{1}{\lambda_i} \ln U_i \tag{2.2}$$

where λ_i is the failure rate of the *i*th component if the present state is the up state; otherwise λ_i is the repair rate of the *i*th component if the present state is the down state.

Step 3. The sampling values of the state durations are obtained for all components by repeating Step 2. The chronological component state transition processes for each component in the given time are then developed.

Step 4. The chronological system state transition processes can be obtained by combining the chronological component state transition processes.

Step 5. System analysis is performed for each different system state to determine the reliability indices.

Step 6. Steps 1-5 are repeated for the desired number of simulations or until the stopping criterion is reached.

This method can be used to calculate the actual frequency and requires more computer time and storage than the state sampling methods.

There are advantages and disadvantages in each of the three simulation approaches. The state sampling method is relatively simple and requires comparatively less reliability data as only the state probability of the component is required. This method provides an upper boundary on the actual frequency index using the sum of the occurrences of the load curtailment states. The state transition sampling approach can offer an exact frequency index in the absence of sampling the distribution function and storing the chronological information required in the sequential approach. This approach, however, only applies to system components with exponentially distributed state durations. The sequential technique can be used to calculate the actual frequency index and can consider any state duration distribution. This technique, however, requires more calculation time and computer storage than the other methods. Another disadvantage is that this method requires reliability parameters related to all the component state duration distributions and it could be difficult to provide all these data for an actual power system.

2.3 Reliability Indices in Composite System Reliability Evaluation

The reliability of a composite system can be represented by a wide range of load point and system indices, as noted earlier. Both load point and system indices are necessary to provide a complete assessment of composite system adequacy and can be categorized as annualized and annual indices. Annualized reliability indices are evaluated using a single load level in a one-year period. The system peak load is normally used. Annualized indices require less computing time and can provide satisfactory indications when comparing the reliabilities of different reinforcement alternatives. Annual reliability indices, however, are calculated based on the actual time-varying load throughout the year. These indices include the expected unsupplied energy and can be used to determine the expected damage costs for the system and are therefore the most valuable and frequently utilized. The basic adequacy indices [2, 3] used in composite system studies are as follows.

Basic indices

(1) Probability of Load Curtailment (PLC)

$$\text{PLC}= \sum_{i \in S} p_i \tag{2.3}$$

where p_i is the probability of system state i and S is the set of all system states associated with load curtailments.

(2) Expected Frequency of Load Curtailment (EFLC)

$$\text{EFLC} = \sum_{i \in S} (F_i - f_i) \quad \text{occ./yr} \tag{2.4}$$

where F_i is the frequency of departing system state i and f_i is the portion of F_i which corresponds to not going through the boundary wall between the loss-of-load state set and the no-loss-of-load state set.

It is difficult to evaluate the frequency index when utilizing the state sampling technique in composite system adequacy assessment. This is because that for each load curtailment state i, it is necessary to identify all the no-load-curtailment states which can be reached from state i in one transition. The Expected Number of Load Curtailments (ENLC) is often used to replace the EFLC index.

$$\text{ENLC} = \sum_{i \in S} F_i \quad \text{occ./yr} \tag{2.5}$$

The ENLC is the sum of the occurrences of the load curtailment states and is therefore an upper bound of the actual frequency index. The system state frequency F_i can be calculated by the following relationship between the frequency and the system state probability p_i:

$$F_i = p_i \sum_{k \in N} \lambda_k \quad \text{occ./yr} \tag{2.6}$$

where λ_k is the departure rate of component corresponding to system state i and N is the set of all possible departure rates corresponding to state i.

(3) Expected Duration of Load Curtailment (EDLC)

$$\text{EDLC} = \text{PLC} \times 8760 \quad \text{hrs/yr} \tag{2.7}$$

(4) Average Duration of Load Curtailment (ADLC)

$$\text{ADLC} = \text{EDLC}/\text{EFLC} \quad \text{hrs/disturbance} \tag{2.8}$$

(5) Expected Load Curtailments (ELC)

$$\text{ELC} = \sum_{i \in S} C_i F_i \quad \text{MW/yr} \tag{2.9}$$

where C_i is the load curtailment of system state i.

(6) Expected Demand Not Supplied (EDNS)

$$\text{EDNS} = \sum_{i \in S} C_i p_i \quad \text{MW} \tag{2.10}$$

(7) Expected energy not supplied (EENS)

$$\text{EENS} = \sum_{i \in S} C_i F_i D_i = \sum_{i \in S} 8760 C_i p_i \quad \text{MWh/yr} \tag{2.11}$$

where D_i is the duration of system state i. This is an important index in composite system adequacy assessment.

(8) Expected damage cost (EDC)

$$\text{EDC} = \sum_{i \in S} C_i F_i D_i W \qquad \text{k\$/yr} \tag{2.12}$$

where C_i is the load curtailment of system state i; F_i and D_i are the frequency and the duration of system state i; W is the unit damage cost in $/kWh.

IEEE-proposed indices

(9) Bulk power interruption index (BPII)

$$\text{BPII} = \frac{\sum_{i \in S} C_i F_i}{L} \qquad \text{MW/MW-yr} \tag{2.13}$$

where L is the annual system peak load in MW.

(10) Bulk power/energy curtailment index (BPECI)

$$\text{BPECI} = \frac{\text{EENS}}{L} \qquad \text{MWh/MW-yr} \tag{2.14}$$

(11) Bulk Power-supply average MW curtailment index (BPACI)

$$\text{BPACI} = \frac{\text{ELC}}{\text{EFLC}} \qquad \text{MW/disturbance} \tag{2.15}$$

(12) Modified bulk energy curtailment index (MBECI)

$$\text{MBECI} = \frac{\text{EDNS}}{L} \qquad \text{MW/MW} \tag{2.16}$$

(13) Severity Index (SI)

$$\text{SI} = \text{BPECI} \times 60 \qquad \text{system min/yr} \tag{2.17}$$

The basic indices (1) to (8) can be applied to an individual load bus or to the entire system. The IEEE-proposed indices (9) to (13) are calculated from the basic indices given by Equations 2.3 to 2.12. These indices can be expressed as annualized or annual values. The advantage of the IEEE-proposed indices is that they can be used to compare the adequacies of systems with different sizes. The basic indices introduced in this section are utilized throughout this thesis.

2.4 Introduction to MECORE

The MECORE program is a composite generation and transmission system reliability evaluation tool based on Monte Carlo simulation. This software was initially developed at the University of Saskatchewan and enhanced at BC Hydro. It can be utilized to perform reliability and reliability worth evaluation of generation systems, transmission systems or bulk power systems. The MECORE software can provide a wide range of reliability indices at the individual load points and for the overall composite system as well as the unreliability cost indices, which reflect reliability worth. The indices created by the program can provide useful information when comparing different planning alternatives from a reliability point of view. The program is based on a combination of state sampling Monte Carlo simulation and enumeration techniques. The Monte Carlo technique is used to simulate the system component states and to calculate annualized indices at the system peak load level. A hybrid method utilizing an enumeration approach for aggregated load states is used to calculate annual indices considering the annual load curve.

The capabilities of the MECORE program are referred to in [31] and brief described as follows:

- System size: 1000 buses and 2000 branches

Limiting the system size to 200-300 buses can be used to provide efficient, quick and accurate calculations.

- Failure modes:
  - Independent failures of generators, lines and transformers
  - Common cause outages of transmission lines
  - Generating unit derated states
- Failure criteria:
  - Capacity deficiency
  - Line overload
  - System separation - load loss
  - Bus isolation - load loss
- Load model:
  - Annual, seasonal, and monthly load curve

- Multi-step models
- Bus load proportional scaling and flat level model

■ Probability indices:
- System and bus indices
- Annualized and monthly/seasonal/annual indices
- Basic and IEEE-proposed indices

The basic indices include the PLC, ENLC, EDLC, ADLC, ELC, EDNS, EENS, EDC given in Equations (2.3), (2.5), (2.7) - (2.12). The IEEE-proposed indices introduced earlier include the BPII, BPECI, BPACI, MBECI, and SI given in Equations (2.13) - (2.17). The ENLC, PLC, ELC, EDNS, and EENS are calculated for each individual load point, and the ENLC, ADLC, EDLC, PLC, EDNS, EENS, EDC, BPII, BPECI, BPACI, MBECI, and SI are calculated at the system level.

■ Linear programming optimization model

The MECORE program utilizes a linear programming Optimal Power Flow (OPF) model to reschedule generation (change generation patterns), alleviate line overloads and avoid load curtailments if possible or minimize total load curtailments if unavoidable. Load curtailment philosophies in the form of a curtailment priority list can be considered in the minimization model. If the load priority order is not specified using priority codes, the program decides the load curtailment order automatically.

2.5 Two Composite Test Systems

Two composite test systems are utilized in the research described in this thesis. They are the Roy Billinton Test System (RBTS) [32] and the IEEE Reliability Test System (IEEE-RTS) [33]. The single line diagrams of the RBTS and the IEEE-RTS are shown in Figures 2.1 and 2.2 respectively.

The RBTS is a small composite test system developed at the University of Saskatchewan for educational and research purposes. The RBTS is a six-bus composite system with five load buses. There are eleven generators located at two generator buses and nine transmission lines. The maximum and the minimum ratings of the generating units are 40 MW and 5 MW respectively. The system voltage level is 230 kV. The total installed generating capacity is 240 MW and the system peak load is 185 MW.

The IEEE-RTS is relatively large compared to the RBTS and was developed by an IEEE Task Force. It includes the reliability parameters of the generation and transmission facilities as well as a comprehensive load model. The generating system contains 32 units located at 10 generator buses, ranging from 12 MW to 400 MW. The transmission system has 24 buses, which include 10 generator buses, 10 load buses, and 4 connection buses, connected by 33 transmission lines and 5 autotransformers at two voltage levels: 138kV and 230kV. The total installed capacity of the IEEE-RTS is 3405 MW and the system peak load is 2850 MW.

The per-unit load model for the IEEE-RTS is also used in RBTS analysis. This load model can be used to create 8760 hourly chronological loads on a per unit basis. The basic data for the two test systems are given in Appendix A.

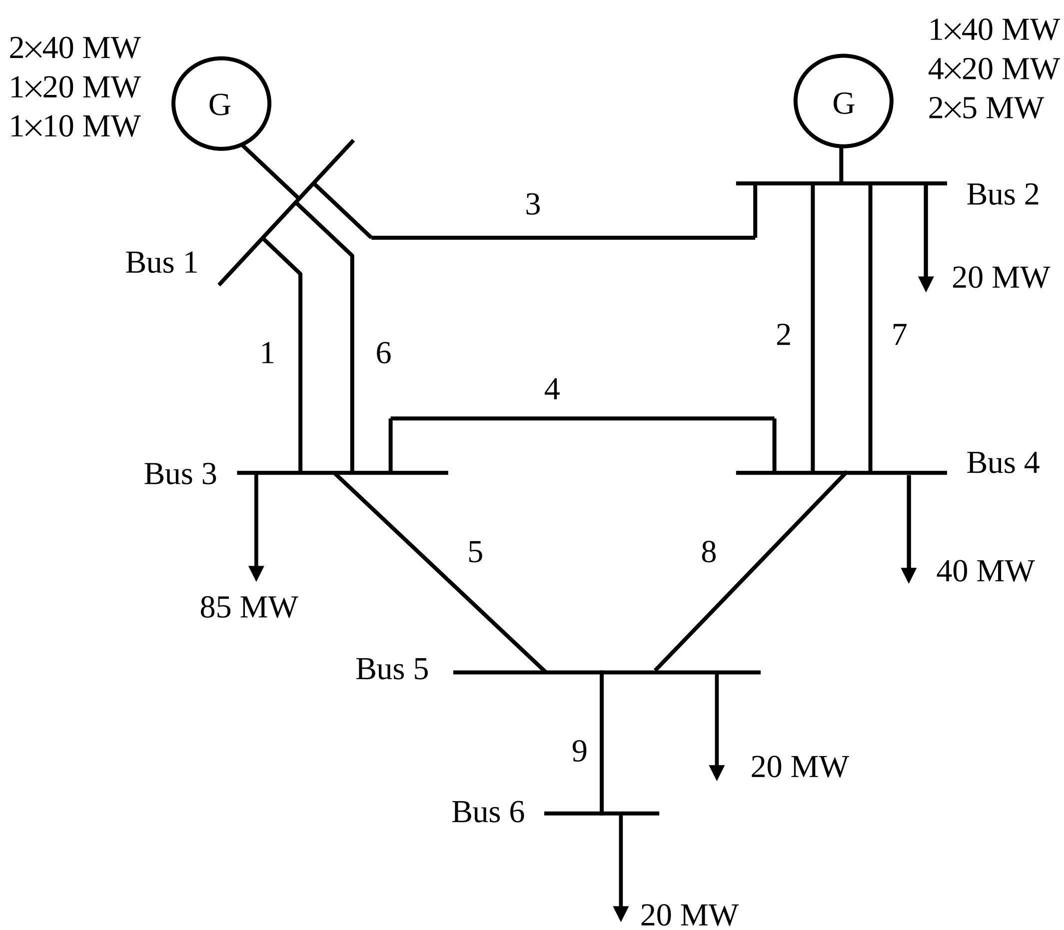

Figure 2.1: Single line diagram of the RBTS

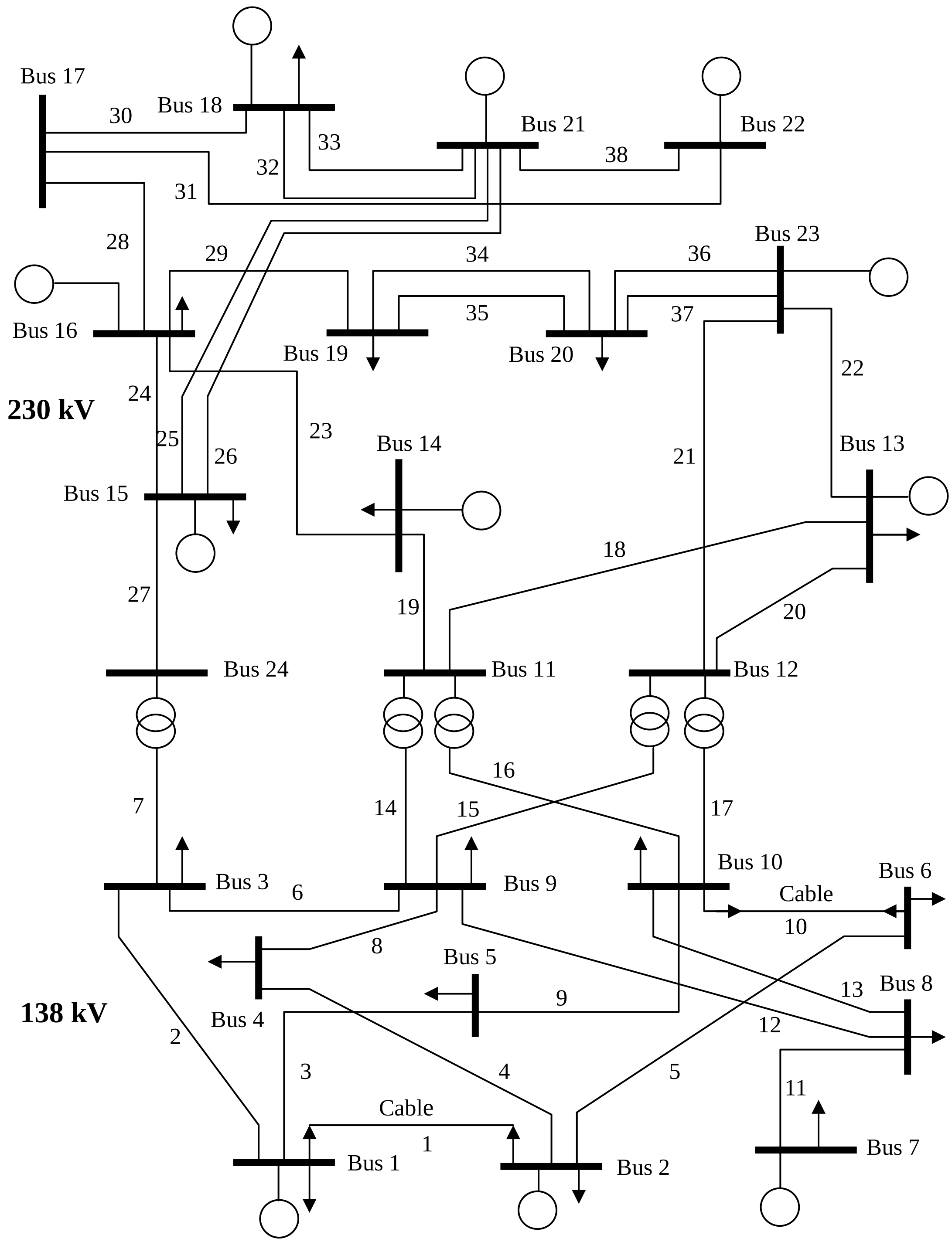

Figure 2.2: Single line diagram of the IEEE-RTS

2.6 Original Test System Reliability Analysis

The reliability analysis of the original RBTS and IEEE-RTS provides a reference for further studies on the two test systems. Many considerations can be included in a composite system reliability evaluation, such as economic priority order for load curtailment, common mode failures of transmission lines, impacts of system alternatives including station configurations and unavailability effects and so on. Some of these factors are considered in this section while others are included in further studies of the two composite test systems.

Both load point and system indices are used to assess composite system adequacy. Load point indices indicate the reliability at the individual load buses while system indices provide an overall evaluation of total system reliability and reliability worth. Two types of reliability indices, annualized and annual indices can be evaluated for the load point and for the total system. The former is calculated at the peak load level and expressed on a one-year basis. The latter is obtained using the annual load duration curve. The annual indices use a fifteen-step load model in the reliability studies of the RBTS and the IEEE-RTS presented in this thesis.

The number of simulation samples should be selected carefully in order to obtain meaningful reliability results. Studies conducted earlier [20] show that acceptable accuracy can be achieved when the numbers of samples for the RBTS and the IEEE-RTS are 2,000,000 and 500,000 respectively. These sample sizes are used in the reliability analyses in this thesis.

Economic priority order in the RBTS and IEEE-RTS

The MECORE software has the capability to consider system load curtailment philosophies using a specified priority order. In actual power systems, each load bus has a different priority for system load curtailment. The load bus priority order affects the individual load point reliabilities in a bulk power system. It is therefore necessary to include the load curtailment priority order in a complete reliability assessment. The priority order of each load point can be based on economic factors that recognize the customer costs associated with failure of supply. The interrupted energy assessment rate (IEAR) can be used to determine the priority order for load curtailment, as it measures the customer monetary loss as a function of the energy not supplied [2]. The lower the value of the IEAR, the lower priority the bus has.

The IEAR values for each load point in the RBTS are shown in Table 2.1 and the corresponding priority order is given in Table 2.2.

Table 2.1: IEAR values of each bus in the RBTS

Bus No.	IEAR ($/kWh)
2	7.41
3	2.69
4	6.78
5	4.82
6	3.63

Table 2.2: Priority order of each bus in the RBTS

Priority Order	Bus No.
1	2
2	4
3	5
4	6
5	3

The IEAR values of each load bus in the IEEE-RTS are given in Table 2.3 and the corresponding priority order is shown in Table 2.4.

Table 2.3: IEAR values of each bus in the IEEE-RTS

Bus No.	IEAR ($/kWh)
1	6.20
2	4.89
3	5.30
4	5.62
5	6.11
6	5.50
7	5.41
8	5.40
9	2.30
10	4.14
13	5.39
14	3.41
15	3.01
16	3.54
18	3.75
19	2.29
20	3.64

Table 2.4: Priority order of each bus in the IEEE-RTS

Priority Order	Bus No.
1	1
2	5
3	4
4	6
5	7
6	8
7	13
8	3
9	2
10	10
11	18
12	20
13	16
14	14
15	15
16	9
17	19

The Expected Damage Cost (EDC) is an important system index that can be used to perform economic analysis on a composite system. MECORE calculates this index by multiplying the EENS of the overall system by the system IEAR calculated using the following equation [19].

$$\text{Aggregate system IEAR} = \sum_{k=1}^{NB} IEAR_k q_k \ \$/\text{kWh} \tag{2.18}$$

where NB is the total number of load buses in the system,

$IEAR_k$ is the Interrupted Energy Assessment Rate (IEAR) at bus k,

q_k is the fraction of the system load utilized by the customers at bus k.

The aggregate system IEAR for the RBTS is 4.42 $/kWh, calculated using the data in Table 2.1 and Table A.1. The overall system IEAR for the IEEE-RTS is 4.22 $/kWh and can be calculated using the data in Table 2.3 and Table A.4.

The effects of load curtailment priority order and the aggregate system IEAR are included in the following adequacy evaluations of the RBTS and the IEEE-RTS.

Reliability analysis of the original RBTS

The annualized and annual load point indices of the RBTS are evaluated utilizing the above information and are shown in Tables 2.5 and 2.6 respectively. The annualized and annual system indices are given in Table 2.7.

Table 2.5: Annualized load point indices of the RBTS

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)
2	0.00000	0.00150	0.004	0.00000	0.044
3	0.00869	4.08024	48.162	0.09699	849.637
4	0.00003	0.02135	0.142	0.00013	1.113
5	0.00004	0.03020	0.300	0.00033	2.888
6	0.00139	1.30199	24.081	0.02471	216.460

Table 2.6: Annual load point indices of the RBTS

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)
2	0.00000	0.00000	0.000	0.00000	0.000
3	0.00018	0.10162	1.171	0.00201	17.564
4	0.00000	0.00109	0.008	0.00000	0.038
5	0.00000	0.00554	0.059	0.00003	0.296
6	0.00120	1.18265	15.095	0.01535	134.452

Table 2.7: Annualized and annual system indices of the RBTS

Indices	Annualized	Annual
ENLC (1/yr)	5.25586	1.27965
ADLC (hrs/disturbance)	16.48	9.45
EDLC (hrs/yr)	86.61	12.09
PLC	0.00989	0.00138
EDNS (MW)	0.12216	0.01739
EENS (MWh/yr)	1070.141	152.350
EDC (k$/yr)	N/A	673.386
BPII (MW/MW-yr)	0.39292	0.08829
BPECI (MWh/MW-yr)	5.785	0.824
BPACI (MW/disturbance)	13.830	12.764
MBECI (MW/MW)	0.00066	0.00009
SI (system minutes/yr)	347.07	49.41

It can be seen from Tables 2.5 and 2.6 that the EENS values of load buses 3 and 6 are much larger than those of the other load buses. These two buses are the least reliable load points in the RBTS. The reason is that Bus 3 has the lowest priority and Bus 6 has the second lowest priority among all the load buses shown in Table 2.2. Bus 6 has the highest EENS because Bus 6 is connected to the rest of the system by a single radial line and is relatively far from the generating units as shown in Figure 2.1.

Reliability analysis of the original IEEE-RTS

The annualized and annual load point indices of the IEEE-RTS are shown in Tables 2.8 and 2.9 respectively. The annualized and annual system indices are given in Table 2.10.

Table 2.8: Annualized load point indices of the IEEE-RTS

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)
1	-	-	-	-	-
2	0.00022	0.21533	7.517	0.00743	65.052
3	0.00012	0.12469	5.997	0.00579	50.685
4	-	-	-	-	-
5	-	-	-	-	-
6	-	-	-	-	-
7	0.00000	0.00327	0.082	0.00005	0.438
8	0.00000	0.00294	0.062	0.00004	0.368
9	0.05080	35.32409	2612.315	3.86918	33894.023
10	0.00056	0.50498	35.025	0.03860	338.171
13	0.00003	0.03218	1.463	0.00126	11.073
14	0.01217	9.29683	639.791	0.81732	7159.724
15	0.03938	25.78817	2481.552	3.48197	30502.036
16	0.00552	4.43487	178.765	0.21584	1890.757
18	0.00237	1.90038	174.843	0.20937	1834.097
19	0.08419	58.09929	4160.458	5.99921	52553.046
20	0.00351	2.93097	153.836	0.18786	1645.678

The EENS at load buses 9, 14, 15 and 19 are larger than those at the other buses in the IEEE-RTS as shown in Tables 2.8 and 2.9. These four buses have the lowest four priorities, as shown in Table 2.4. The priority order strongly affects the individual load point reliability indices.

The load curtailment priority order has a significant effect on the individual load bus indices. Studies have shown that it has a comparatively small effect on the overall system indices [20]. It can also be seen that the annual indices are much lower than the annualized indices since the actual load model is used in calculating the annual indices.

Table 2.9: Annual load point indices of the IEEE-RTS

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)
1	-	-	-	-	-
2	0.00000	0.00140	0.049	0.00005	0.397
3	0.00000	0.00082	0.027	0.00002	0.215
4	-	-	-	-	-
5	-	-	-	-	-
6	0.00000	0.00075	0.052	0.00003	0.293
7	0.00000	0.00041	0.004	0.00000	0.021
8	0.00000	0.00004	0.000	0.00000	0.002
9	0.00113	0.87165	53.880	0.06935	607.472
10	0.00001	0.00535	0.295	0.00029	2.541
13	0.00000	0.00013	0.004	0.00000	0.031
14	0.00021	0.17742	10.795	0.01266	110.899
15	0.00067	0.52376	45.318	0.05604	490.941
16	0.00010	0.08251	3.165	0.00362	31.750
18	0.00003	0.03086	2.402	0.00255	22.376
19	0.00201	1.51929	96.376	0.12820	1123.034
20	0.00006	0.05564	2.484	0.00273	23.956

Note: The indices at some buses are too small to be observed by MECORE and are marked with a -.

Table 2.10: Annualized and annual system indices of the IEEE-RTS

Indices	Annualized	Annual
ENLC (1/yr)	58.10550	1.52049
ADLC (hrs/disturbance)	12.691	11.564
EDLC (hrs/yr)	737.504	17.584
PLC	0.08419	0.00201
EDNS (MW)	14.833	0.276
EENS (MWh/yr)	129932.7	2413.923
EDC (k$/yr)	N/A	10186.755
BPII (MW/MW-yr)	3.66724	0.07539
BPECI (MWh/MW-yr)	45.590	0.847
BPACI (MW/disturbance)	179.873	141.305
MBECI (MW/MW)	0.00520	0.00010
SI (system minutes/yr)	2735.426	50.819

The annual reliability indices are used to evaluate the reliability performance in the subsequent studies described in this thesis. The load curtailment philosophy used in the previous studies was applied throughout this research.

2.7 Basic Studies on the Two Composite Test Systems

2.7.1 RBTS Analysis

RBTS with generating unit transformers

In a practical power system, a generator is connected to the transmission network by a transformer. In some cases, two or more generators share the same step-up transformer. In the RBTS, generators 8 and 9 share a single transformer as well as generators 10 and 11. The extended RBTS with generating unit transformers are shown in Figure 2.3. Load point step-down transformers are not included in this assessment.

The generating unit forced outage rate includes the transformer unavailability [32]. The individual element reliability data for the generating unit and the transformer are obtained as follows, using the input data for a 40 MW thermal generating unit.

The reliability data for the station transformer is

Failure rate = 0.02 f/yr   Outage duration = 768 hrs

Therefore, the unavailability of the transformer is

$U_t = 0.02/(0.02+8760/768) \approx 0.00175$

The generator and the transformer are in series, therefore the unavailability of the generating unit is

$U_g \approx U_{total\ unit}-U_t = 0.03-0.00175 = 0.02825$

The mean time to repair (MTTR) of the generating unit is

$r_g \approx 8760*0.02825/(6-0.02) = 41.38294$ hr

The data for the other generating units and transformers are modified using the same method. The modified generator data are shown in Table A.10.

The annual indices for the load bus and the overall RBTS with generating unit transformers are shown in Tables 2.11 and 2.12.

Table 2.11: Annual load point indices of the RBTS (base case)

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)
2	0.00000	0.00000	0.000	0.00000	0.000
3	0.00019	0.10696	1.227	0.00212	18.579
4	0.00000	0.00103	0.007	0.00000	0.031
5	0.00000	0.00549	0.059	0.00003	0.289
6	0.00120	1.18543	15.128	0.01535	134.463

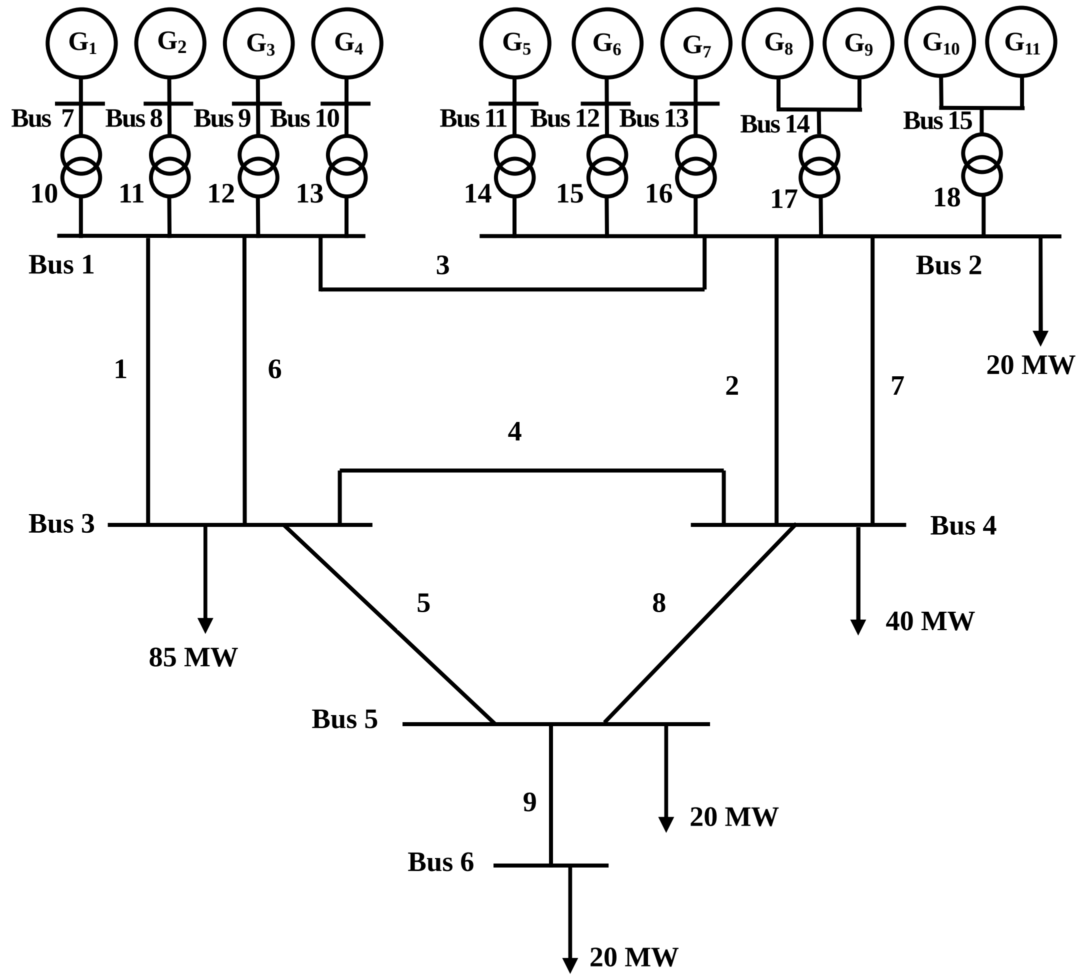

Figure 2.3: Extended single line diagram of the RBTS with generating unit transformers

Table 2.12: Annual system indices of the RBTS (base case)

Indices	Values
ENLC (1/yr)	1.28750
ADLC (hrs/disturbance)	9.47
EDLC (hrs/yr)	12.19
PLC	0.00139
EDNS (MW)	0.018
EENS (MWh/yr)	153.362
EDC (k$/yr)	677.859
BPII (MW/MW-yr)	0.08877
BPECI (MWh/MW-yr)	0.829
BPACI (MW/disturbance)	12.755
MBECI (MW/MW)	0.00009
SI (system minutes/yr)	49.74

There are very slight differences in the load point and system indices due to the modifications made at Buses 14 and 15 in Figure 2.3. The differences can be seen by comparing the results in Tables 2.11 and 2.12 with those in Tables 2.6 and 2.7.

RBTS with generating unit transformers and load point transformers

The RBTS including load point step-down transformers is shown in Figure 2.4. The reliability data of the load point transformers is the same as that of the generating unit transformers. It is assumed that each load bus has only one step-down transformer owned by the electric power utility. The annual load point and system indices for the RBTS with generating unit and load point transformers are shown in Tables 2.13 and 2.14.

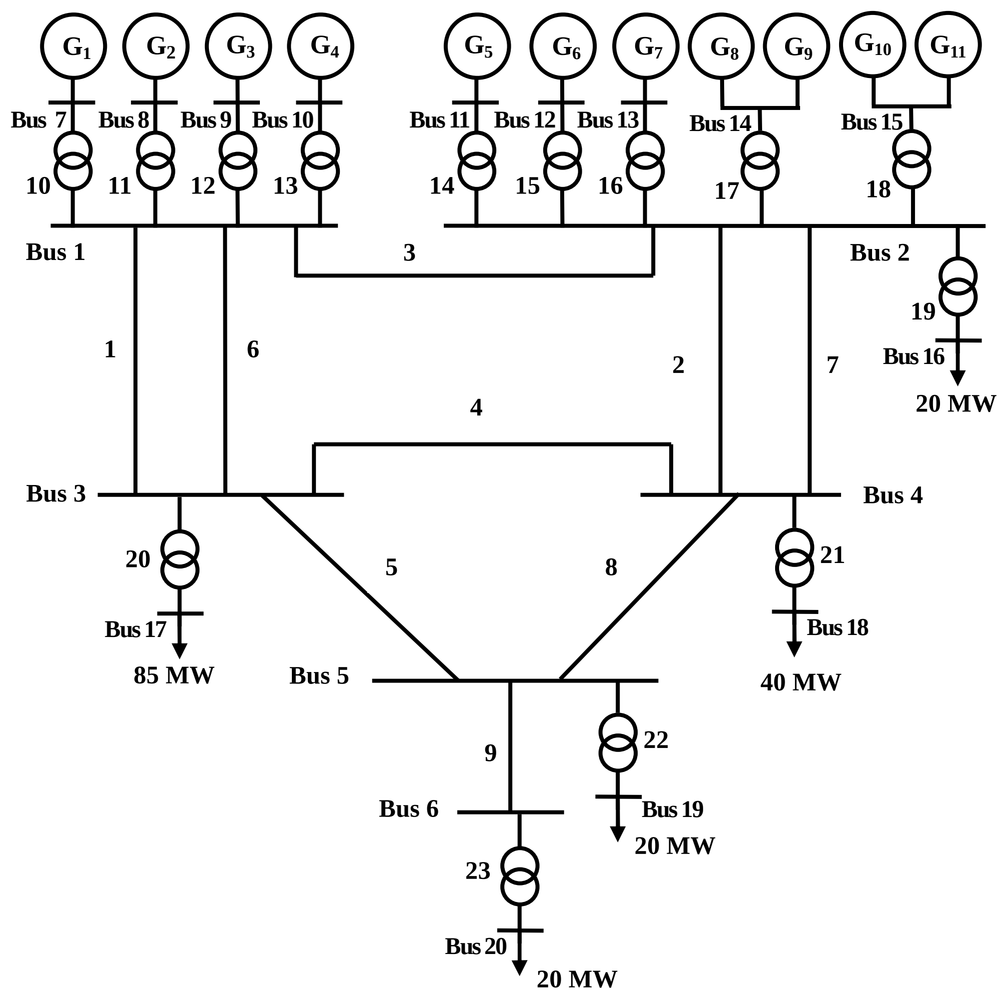

Figure 2.4: Extended single line diagram of the RBTS with load point transformers

Table 2.13: Annual load point indices of the RBTS (Figure 2.4)

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)
16	0.00175	0.21835	2.793	0.02240	196.224
17	0.00197	0.33849	13.860	0.09880	865.447
18	0.00178	0.23105	5.892	0.04558	399.315
19	0.00175	0.23387	2.981	0.02232	195.561
20	0.00300	1.41006	17.918	0.03826	335.159

Table 2.14: Annual system indices of the RBTS (Figure 2.4)

Indices	Values
ENLC (1/yr)	2.41085
ADLC (hrs/disturbance)	37.07
EDLC (hrs/yr)	89.379
PLC	0.01020
EDNS (MW)	0.227
EENS (MWh/yr)	1991.710
EDC (k$/yr)	8803.338
BPII (MW/MW-yr)	0.23484
BPECI (MWh/MW-yr)	10.766
BPACI (MW/disturbance)	18.021
MBECI (MW/MW)	0.00123
SI (system minutes/yr)	645.958

The reliability indices for the load point and the overall system increase considerably by incorporating the load point transformers, as can be seen by compared Tables 2.13 and 2.14 with Tables 2.11 and 2.12. It shows that the step-down transformer is a major contribution to the unreliability of a connected load point as it is in series with the load point.

RBTS with common mode failures

A common mode outage is an event having a single external cause with multiple failure effects which are not consequences of each other [19]. In a transmission system, common mode failure events generally occur on those transmission lines which use a common right-of-way or common tower. The MECORE program has the ability to incorporate common mode failures of transmission lines. The common mode data for the RBTS [32] are shown in Table 2.15. The annual load point and system indices in Tables 2.16 and 2.17 show the effects of common mode failures on the reliability performance of the RBTS. These results also include the effects of generation and load point transformers.

Table 2.15: Common mode data for the RBTS

Buses		Line	Common length (km)	Failure rate (occ/yr)	Outage duration (hr)
From	To				
1	3	1	75	0.150	16.0
1	3	6			
2	4	2	250	0.500	16.0
2	4	7			

Table 2.16: Annual load point indices of the RBTS (including common mode failures)

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)
16	0.00175	0.26276	3.354	0.02240	196.224
17	0.00200	0.42645	17.677	0.09915	868.541
18	0.00178	0.28168	7.114	0.04560	399.484
19	0.00175	0.28922	3.650	0.02234	195.731
20	0.00300	1.50465	19.073	0.03829	335.386

Table 2.17: Annual system indices of the RBTS (including common mode failures)

Indices	Values
ENLC (1/yr)	2.69481
ADLC (hrs/disturbance)	33.25
EDLC (hrs/yr)	89.595
PLC	0.01023
EDNS (MW)	0.228
EENS (MWh/yr)	1995.366
EDC (k$/yr)	8819.516
BPII (MW/MW-yr)	0.275
BPECI (MWh/MW-yr)	10.786
BPACI (MW/disturbance)	18.876
MBECI (MW/MW)	0.00123
SI (system minutes/yr)	647.146

The load point and system indices increase slightly by considering the effect of common mode failures compared with the results in Tables 2.13 and 2.14. Common mode failures of transmission lines can, however, have a big impact on the reliability indices when the system has many transmission lines on common tower structures. The frequency of common cause outages and the system configuration play an important role in the overall system reliability performance.

2.7.2 IEEE-RTS Analysis

IEEE-RTS with generating unit transformers

The extended IEEE-RTS with generating unit transformers and load point transformers is shown in Figure 2.5 [28]. The load point transformers shown in this figure are not included in this initial reliability analysis. The transformer data are the same as those in the RBTS. The modified generator data are shown in Tables A.11. The annual load point and overall system indices for the IEEE-RTS with generating unit transformers are shown in Tables 2.18 and 2.19.

There is a slight difference in the load point and system indices due to separating the generating unit transformers from the generating units. This can be seen by comparing the results in Tables 2.18 and 2.19 with those in Tables 2.9 and 2.10. The difference is basically due to the process of simulation.

Table 2.18: Annual load point indices for the IEEE-RTS (base case)

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)
1	-	-	-	-	-
2	0.00000	0.00143	0.053	0.00004	0.386
3	0.00000	0.00094	0.032	0.00003	0.223
4	-	-	-	-	-
5	-	-	-	-	-
6	0.00000	0.00080	0.056	0.00003	0.293
7	0.00000	0.00043	0.004	0.00000	0.020
8	0.00000	0.00009	0.001	0.00000	0.004
9	0.00111	0.93425	57.799	0.06873	602.035
10	0.00000	0.00536	0.307	0.00027	2.388
13	0.00000	0.00017	0.006	0.00000	0.041
14	0.00021	0.18753	11.397	0.01236	108.304
15	0.00065	0.55726	48.347	0.05527	484.203
16	0.00009	0.08824	3.330	0.00353	30.930
18	0.00003	0.03214	2.483	0.00243	21.298
19	0.00199	1.63121	103.282	0.12687	1111.382
20	0.00006	0.05773	2.555	0.00260	22.733

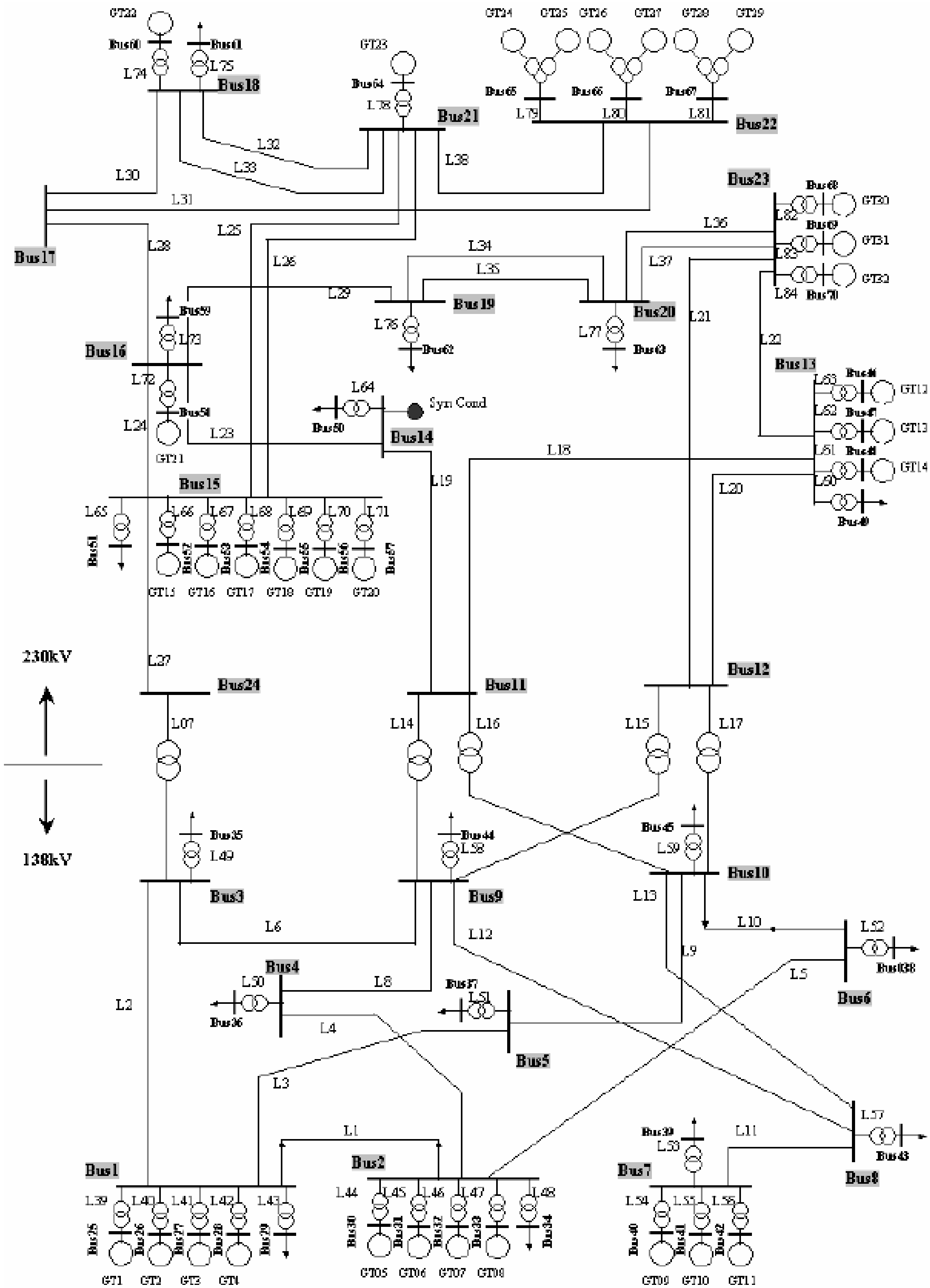

Figure 2.5: Extended single line diagram of the IEEE-RTS

Table 2.19: Annual system indices for the IEEE-RTS (base case)

Indices	Values
ENLC (1/yr)	1.63246
ADLC (hrs/disturbance)	10.67693
EDLC (hrs/yr)	17.43
PLC	0.00199
EDNS (MW)	0.27217
EENS (MWh/yr)	2384.23
EDC (k$/yr)	10061.47
BPII (MW/MW-yr)	0.081
BPECI (MWh/MW-yr)	0.837
BPACI (MW/disturbance)	140.68
MBECI (MW/MW)	0.00010
SI (system minutes/yr)	50.19

IEEE-RTS with generating unit transformers and load point transformers

The extended IEEE-RTS with generating unit transformers and load point transformers is shown in Figure 2.5. The load point transformers are now included in the reliability analysis using the same data as in the RBTS. Each load bus has only one step-down transformer, which is assumed to be owned by the electric power utility. The annual load point and overall system indices for the IEEE-RTS with generating unit and load point transformers are shown in Tables 2.20 and 2.21.

Table 2.20: Annual load point indices for the IEEE-RTS (Figure 2.5)

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)
29	0.00171	0.88932	61.434	0.11785	1032.378
34	0.00168	0.89379	55.424	0.10390	910.148
35	0.00172	0.92478	106.420	0.19759	1730.889
36	0.00181	0.95589	45.245	0.08558	749.663
37	0.00168	0.90637	41.162	0.07648	669.941
38	0.00173	0.91041	79.196	0.15084	1321.368
39	0.00176	0.94009	75.135	0.14088	1234.126
43	0.00185	0.99132	108.420	0.20213	1770.661
44	0.00280	1.80243	156.357	0.25823	2262.060
45	0.00177	0.93250	116.000	0.22051	1931.653
49	0.00182	0.99254	168.226	0.30918	2708.387
50	0.00198	1.13438	129.373	0.23251	2036.774
51	0.00239	1.44908	230.947	0.40748	3569.487
59	0.00183	1.00952	62.469	0.11463	1004.136
61	0.00179	0.96251	200.980	0.37753	3307.130
62	0.00379	2.57274	214.970	0.33732	2954.885
63	0.00183	0.98688	78.803	0.14819	1298.115

Table 2.21: Annual system indices for the IEEE-RTS (Figure 2.5)

Indices	Values
ENLC (1/yr)	17.161
ADLC (hrs/disturbance)	15.96706
EDLC (hrs/yr)	274.02
PLC	0.03128
EDNS (MW)	3.48080
EENS (MWh/yr)	30491.802
EDC (k$/yr)	128675.401
BPII (MW/MW-yr)	0.677
BPECI (MWh/MW-yr)	10.699
BPACI (MW/disturbance)	112.50
MBECI (MW/MW)	0.00122
SI (system minutes/yr)	641.93

It can be seen from Tables 2.20 and 2.21 that the load point and system reliability indices for the IEEE-RTS with load point transformers increase considerably, compared with those in Tables 2.18 and 2.19. The load point transformers have a significant impact on the load point and system reliability levels.

IEEE-RTS with common mode failures

The common mode data of the transmission lines in the IEEE-RTS [33] are shown in Table 2.22. The effect of common cause failures was incorporated in an IEEE-RTS reliability evaluation. The annual load point and system reliability indices are shown in Tables 2.23 and 2.24. The generating unit and load point transformers are included in this IEEE-RTS reliability evaluation.

Table 2.22: Common mode data for the IEEE-RTS

Buses		Line	Common length (km)	Failure rate (occ/yr)	Outage duration (hr)
From	To				
15	21	25	34	0.0205	16.0
15	21	26			
18	21	32	18	0.0175	16.0
18	21	33			
19	20	34	27.5	0.0190	16.0
19	20	35			
20	23	36	15	0.0170	16.0
20	23	37			

Table 2.23: Annual load point indices for the IEEE-RTS
(including common mode failures)

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)
29	0.00171	0.97034	67.032	0.11785	1032.379
34	0.00168	0.96278	59.704	0.10390	910.148
35	0.00172	0.98391	113.228	0.19759	1730.889
36	0.00181	1.03204	48.850	0.08558	749.663
37	0.00168	0.97098	44.096	0.07648	669.941
38	0.00173	0.97063	84.435	0.15084	1321.368
39	0.00176	1.02837	82.222	0.14088	1234.106
43	0.00185	1.07127	117.163	0.20213	1770.661
44	0.00281	1.92155	166.731	0.25875	2266.688
45	0.00177	0.99291	123.517	0.22051	1931.666
49	0.00182	1.05933	179.548	0.30918	2708.387
50	0.00198	1.21568	138.495	0.23263	2037.845
51	0.00239	1.56362	250.557	0.40776	3571.962
59	0.00183	1.09027	67.549	0.11463	1004.170
61	0.00179	1.03222	215.722	0.37753	3307.125
62	0.00381	2.75933	230.762	0.33865	2966.548
63	0.00184	1.04994	83.829	0.14820	1298.247

Table 2.24: Annual system indices for the IEEE-RTS
(including common mode failures)

Indices	Values
ENLC (1/yr)	18.462
ADLC (hrs/disturbance)	14.85430
EDLC (hrs/yr)	274.250
PLC	0.03131
EDNS (MW)	3.48308
EENS (MWh/yr)	30511.800
EDC (k$/yr)	128759.800
BPII (MW/MW-yr)	0.728
BPECI (MWh/MW-yr)	10.706
BPACI (MW/disturbance)	112.31
MBECI (MW/MW)	0.00122
SI (system minutes/yr)	642.35

The reliability effect of common mode outages is relatively small for the IEEE-RTS, as this system has a very strong transmission network.

2.8 Summary

This chapter briefly describes the basic concepts and evaluation techniques utilized in composite generation and transmission systems. Bulk system reliability can be evaluated either by analytical techniques or by Monte Carlo simulation methods. Analytical techniques are based on mathematical models and assumptions are usually made to simplify the solutions. Monte Carlo simulation methods can be used to provide accurate frequency and duration indices and to perform assessments that include complex operating conditions.

Three basic Monte Carlo simulation techniques designated as state sampling, state transition sampling and sequential analysis are introduced in this chapter. Each approach has its own advantages and disadvantages. The MECORE program is based on the state sampling approach and is designed to conduct reliability and reliability worth assessments of composite systems. Its capabilities are briefly presented in this chapter. This program has been utilized to conduct all the bulk system reliability studies presented in this thesis.

The reliability of a composite system can be evaluated using the load point and system indices. The load point indices are used to determine the adequacy at the distribution supply points. The system indices provide an overall evaluation of the total system reliability and reliability worth. Both sets of indices can be expressed using annualized or annual values. Annualized indices utilize a constant load level and can be used to compare the reliability performance of different system reinforcement plans. Annual indices incorporate the hourly variations in system load and estimate the actual unsupplied energy and customer damage costs for the system. The annual indices are utilized in further studies. The basic indices and IEEE-proposed indices are also presented in this chapter. The basic indices can be used to measure the reliability of an individual load bus or the entire system, while the IEEE-proposed indices are applied to the total system.

Two composite test systems known as the RBTS and the IEEE-RTS are used in this research. The RBTS is a small system designed for education and research purposes. The IEEE-RTS is relatively large compared to the RBTS. The annualized and annual indices for the original RBTS [32] and IEEE-RTS [33] are given in this chapter.

The original test systems have been extended in this chapter to include some additional considerations in order to provide a framework for the research described later in this thesis. These considerations include the economic priority order, generating unit transformers, load point transformers and common mode failures. The load point and system reliability indices for the composite test systems with generating unit transformers are very close to those for the original systems and are used as base case results in further studies. The studies show that the load point transformers have a significant effect on the load point reliability indices of these two composite test systems. The step-down transformers are not included in the reliability studies in the following chapters. The effect on the load point and system reliability of common mode outages is relatively small in the systems but is dependent on many factors including the number of multi-circuit tower structures in the system.

The single line diagrams shown in Figures 2.3 and 2.5 indicate that the generation, transformation and transmission elements terminate at simple connection points. These connection points can consist of quite complex arrangements of terminal station equipment. These considerations are introduced in the following chapter.

Chapter 3

Incorporating Station Related Maintenance Outages in Composite System Reliability Evaluation

3.1 Introduction

A bulk power system is normally composed of a large number of generators, transmission lines, switching stations and substations. Substations and switching stations (stations) are important elements and are energy transfer points between power sources, transmission lines and customers. The quality and availability of power supply to the customer, therefore, depends on the performance of the station equipment. Failures of station components can cause the forced removal of one or more connected elements from service and affect the adequacy and security of the bulk system. These elements include generators, transformers and transmission lines. Factors considered in selecting a specific station configuration include reliability, operating flexibility and simplicity, protective relaying, equipment maintenance, future extensions and modifications, etc. It is therefore important and necessary to analyze and incorporate station related outages in composite system reliability evaluation. Research has been conducted to incorporate the effects of station originated failures on composite system reliability performance [20-28, 30]. The effects of station related maintenance outages, however, are not considered in most studies.

The major elements of a substation or a switching station are circuit breakers, bus bars and isolators. These elements are periodically removed from service to perform preventive maintenance. Maintenance programs are implemented in electric power systems to keep equipment in a good working condition and prolong their useful life. Failures of other components while maintenance is being performed can have considerable impact on the ability of the station to perform its assigned functions. As noted earlier, there are two basic maintenance philosophies: scheduled maintenance and predictive maintenance [29]. The research in this thesis is mainly focused on scheduled maintenance of station components.

Probabilistic models can be used to incorporate the uncertainties associated with system behavior while conducting station related maintenance outages in a bulk power system. The objective of this research is to develop a probabilistic approach to incorporate station maintenance outages in composite system reliability evaluation. State space models of the individual station components and their application in creating mathematical models of the station failure modes are presented in this chapter. The basic evaluation technique including maintenance outages is described and illustrated using a ring bus station from the RBTS as an example.

3.2 Model Descriptions

Station related outages can affect the adequacy and security of a bulk system by limiting the transfer capability of the connected elements. The primary components in a station considered in this research are circuit breakers, bus bars and transformers. The primary components are removed from service due to random forced outages and scheduled maintenance. The processes of component failure, repair, switching action and preventive maintenance can be represented by state space models. The models for circuit breakers, bus bars and transformers with or without maintenance considerations are derived using the following assumptions. These models are used to incorporate station forced outages and maintenance outages in bulk system reliability evaluation.

The following assumptions are made to simplify the evaluation process.

a) The probability of a circuit breaker stuck failure is assumed to be zero.

b) Preventive maintenance of bus bars is not performed.

c) Disconnects are assumed to be 100% reliable.

d) The probability of overlapping outages of three or more components is negligible.

e) A component other than a generating unit transformer is not taken out for preventive maintenance if it causes the outage of a major component.

The state space models for a circuit breaker and a bus bar and their application in creating mathematical models of the station failure modes are described in the following.

3.2.1 Basic Station Component Models

Basic model of a circuit breaker

The state space model for a circuit breaker is shown in Figure 3.1. Two failure modes, passive failures and active failures are included in this model. Passive failures do not cause the operation of protection breakers and therefore do not have an impact on the remaining healthy components. Passive failures include open circuits and the inadvertent opening of breakers [2]. Active failures cause the operation of the primary protection zone around the failed component and can therefore cause the removal of other healthy components and branches from service. The actively failed component is subsequently isolated and the associated breakers are reclosed.

In Figure 3.1, the transition rate λ_a is the active failure rate and the transition rate λ_p is the passive failure rate. The transition rate μ_{sw} is the switching rate and is the reciprocal of the switching time. The transition rate μ from state 3 to state 1 is the repair rate of the circuit breaker and is the reciprocal of the duration required to restore a failed breaker back to service.

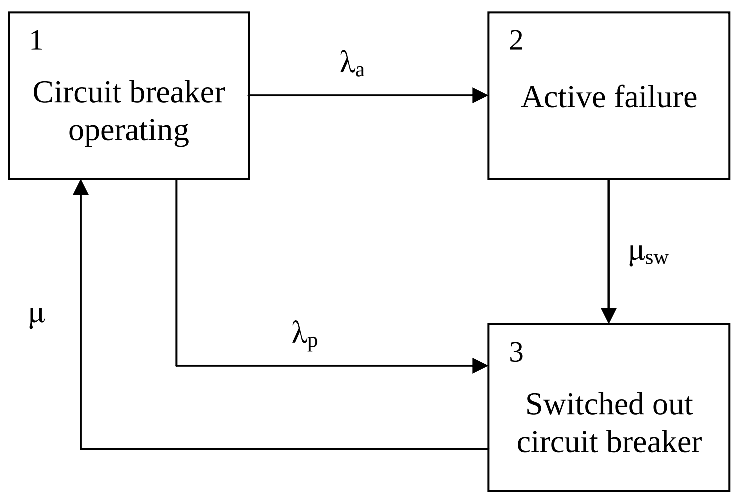

Figure 3.1: State space model of a circuit breaker

Basic model for a bus section

A bus section is used to connect two or more components in a station. The failure of a bus section, therefore, can have considerable impact on the station reliability. The model of a bus bar is shown in Figure 3.2. The transition rate λ_b is the failure rate of the bus bar. The transition rate μ_b is the repair rate and is the reciprocal of the repair time.

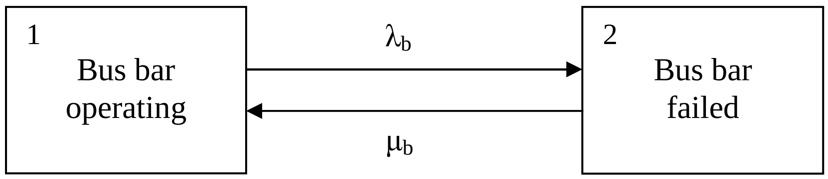

Figure 3.2: State space model of a bus bar

Basic model for a transformer

Transformers are used to increase or reduce voltage levels in an electric power system. The state space model of a transformer is shown in Figure 3.3. The transition rate λ_t is the failure rate of the transformer and the transition rate μ_t is the repair rate.

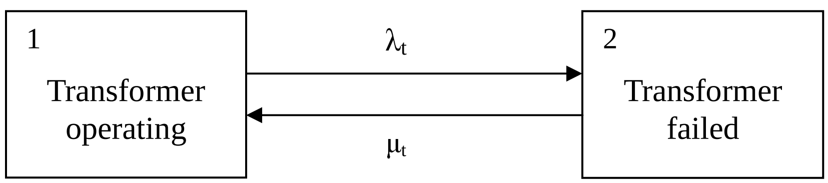

Figure 3.3: State space model of a transformer

Model for station related multiple component outages

Station related outages can force two or more station connected devices out of service. The state space model of such an event is shown in Figure 3.4. The transition rates λ_1 and λ_2 are the failure rates and the transition rates μ_1 and μ_2 are the repair rates of components 1 and 2 respectively. The two system components are out of service in state 5 because of a station related outage. The rate λ_{12} from state 1 to state 5 and the rate μ_{12} from state 5 to state 1 are the common failure and repair rates respectively.

3.2.2 Station Component Models Including Maintenance Outages

State space models for a circuit breaker and a transformer are shown in the following. As noted earlier, preventive maintenance is not performed on bus bars. The model for a bus bar is therefore the same as that shown in Figure 3.2.

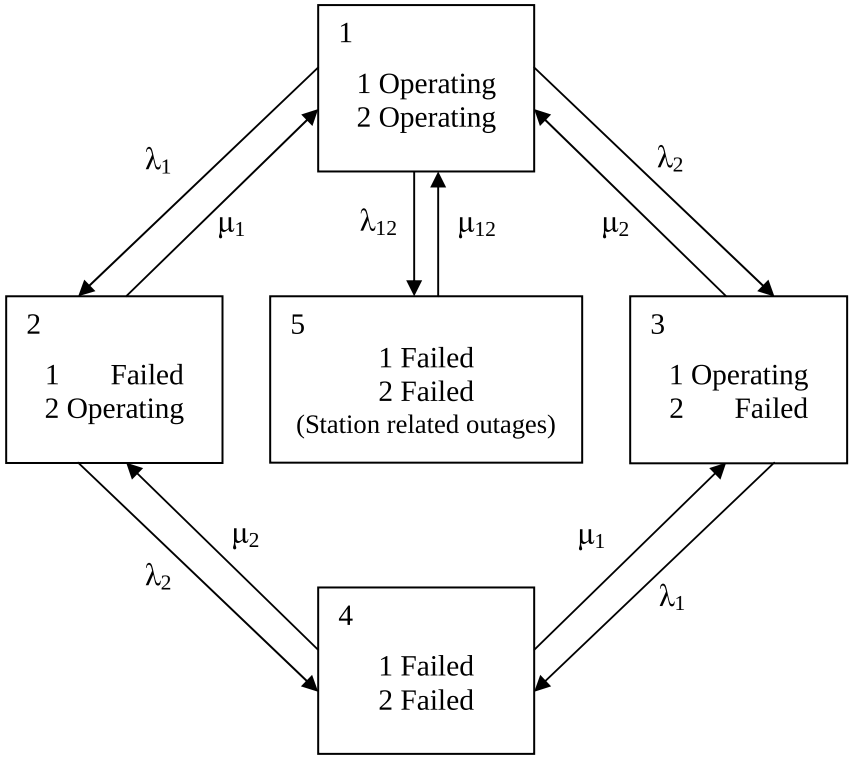

Figure 3.4: Model of two system components
(including a common failure caused by station related outages)

Model for a circuit breaker including maintenance outages

The state space model for a circuit breaker including maintenance outages is shown in Figure 3.5. The transition rate λ'' from state 1 to state 4 is the maintenance outage rate of the circuit breaker. The transition rate μ'' from state 4 to state 1 is the maintenance duration rate and is the reciprocal of the mean time required for a maintained breaker to be restored to service, λ_a is the active failure rate, λ_p is the passive failure rate of the circuit breaker, μ_{sw} is the switching rate and μ is the repair rate.

Model for a transformer with maintenance outages

The state space model for a transformer is shown in Figure 3.6. The transition rate λ_t'' is the maintenance outage rate, and the transition rate μ_t'' is the maintenance duration rate and is the reciprocal of the repair time of the transformer. The transition rate λ_t is the failure rate and μ_t is the repair rate of the transformer.

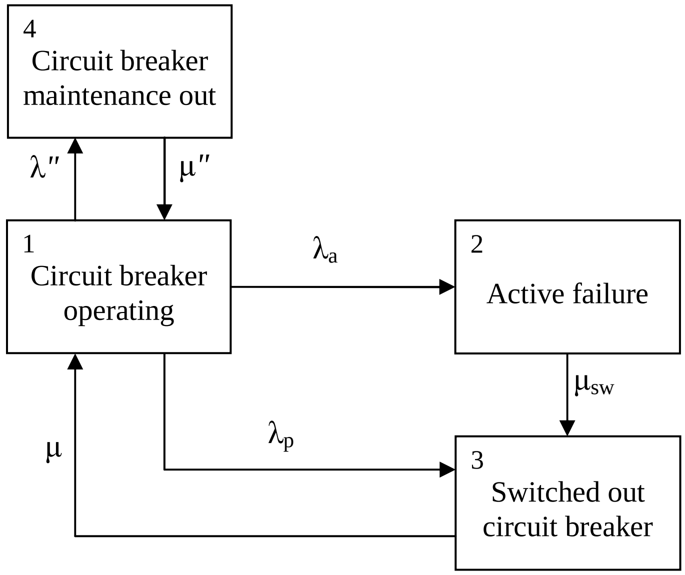

Figure 3.5: Model of a circuit breaker (including maintenance outages)

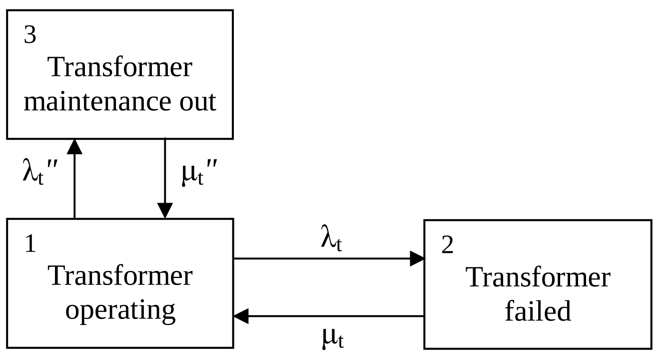

Figure 3.6: Model of a transformer (including maintenance outages)

3.2.3 Evaluation of Station Related Forced Outages

The equations for first and second order station related forced outages are presented in the following.

First order station related outages

(a) Active failure of a circuit breaker

The first order equations for an active circuit breaker failure event are given by (3.1).

$$\begin{aligned} \lambda &= \lambda_a \\ r &= s \\ U &= \lambda_a s \end{aligned} \tag{3.1}$$

where λ, r and U are the event failure rate, repair time and unavailability respectively and λ_a and s are the circuit breaker active failure rate and switching time respectively.

(b) Total failure of a circuit breaker (without considering maintenance outages)

The three-state model of the circuit breaker in Figure 3.1 can be reduced to the two-state model shown in Figure 3.7.

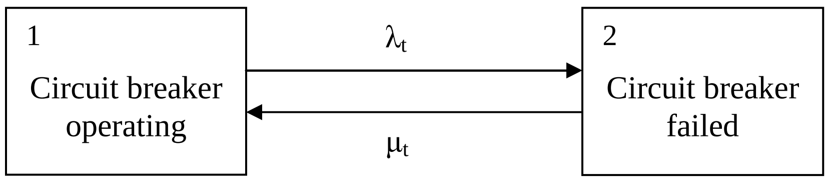

Figure 3.7: Equivalent model of a circuit breaker (without maintenance outages)

The first order equations for a total circuit breaker failure event are given by (3.2).

$$\lambda_t = \lambda_p + \lambda_a$$
$$\mu_t = \frac{P_1 \cdot \lambda_t}{P_2} \qquad r_t = \frac{1}{\mu_t} \tag{3.2}$$
$$U_t = \lambda_t r_t$$

where,

λ_t is the total failure rate of a circuit breaker,

μ_t is the total repair rate of a circuit breaker,

r_t is the average outage duration of a circuit breaker,

U_t is the unavailability of a circuit breaker,

P_1 is the probability of being in the operating state 1,

P_2 is the probability of being in the failed state 2.

Second order station related outages

(a) Two component overlapping forced outages

The models for overlapping forced outage events involving two components are shown in Figure 3.8 and the equations are given by (3.3).

$$\lambda_{pp} = \lambda_1 \lambda_2 (r_1 + r_2)$$
$$U_{pp} = \lambda_1 \lambda_2 r_1 r_2 \tag{3.3}$$
$$r_{pp} = \frac{U_{pp}}{\lambda_{pp}}$$

where,

λ_{pp} is the failure rate of the overlapping failure event,

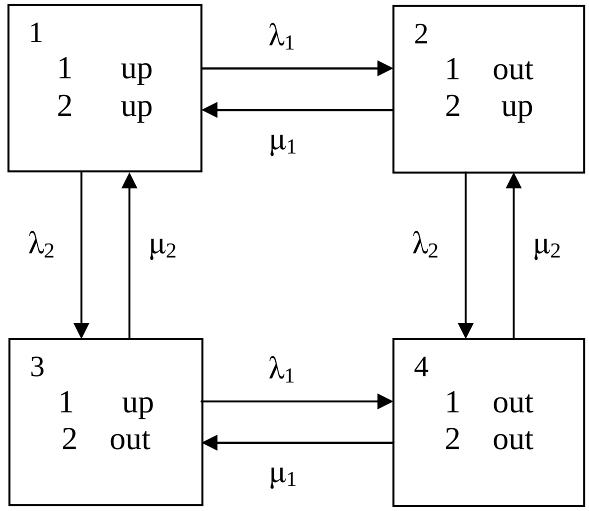

Figure 3.8: Model for two component overlapping forced outages

r_{pp} is the average outage duration of the overlapping failure event,

U_{pp} is the unavailability of the overlapping failure event,

λ_1 is the failure rate of component 1,

λ_2 is the failure rate of component 2,

r_1 is the repair time of component 1,

r_2 is the repair time of component 2.

(b) Active failure of component 1 overlapping the forced outage of component 2

The equations for this overlapping forced outage event are given by (3.4).

$$\begin{aligned} \lambda_{ap} &= \lambda_1^a(\lambda_2 s_1) + \lambda_2(\lambda_1^a r_2) = \lambda_1^a \lambda_2 (s_1 + r_2) \\ r_{ap} &= \frac{s_1 r_2}{s_1 + r_2} \\ U_{ap} &= \lambda_{ap} r_{ap} \end{aligned} \tag{3.4}$$

where,

λ_{ap} is the failure rate of the overlapping failure event,

r_{ap} is the average outage duration of the overlapping failure event,

U_{ap} is the unavailability of the overlapping failure event,

λ_1^a is the active failure rate of component 1,

s_1 is the switching time of component 1 after its active failure,

λ_2 is the failure rate of component 2,

r_2 is the repair time of component 2.

3.2.4 Station Related Maintenance Outages

A station component is periodically taken out for preventive maintenance in order to minimize its failure rate and to prolong its service life. Preventive maintenance is not conducted on a circuit breaker or a bus bar if this will cause other major system components to be removed from service.

(a) Component maintenance outage overlapped by a component forced outage

$$\begin{aligned}
\lambda_{pm} &= \lambda_1''(\lambda_2 r_1'') + \lambda_2''(\lambda_1 r_2'') \\
U_{pm} &= \lambda_1''(\lambda_2 r_1'')\frac{r_1'' r_2}{r_1'' + r_2} + \lambda_2''(\lambda_1 r_2'')\frac{r_1 r_2''}{r_1 + r_2''} \\
r_{pm} &= \frac{U_{pm}}{\lambda_{pm}}
\end{aligned} \tag{3.5}$$

where,

λ_{pm} is the failure rate of the overlapping failure event,

U_{pm} is the unavailability of the overlapping failure event,

r_{pm} is the average outage duration of the overlapping failure event,

λ_1'' and r_1'' are the maintenance rate and maintenance duration of component 1 respectively,

λ_2'' and r_2'' are the maintenance rate and maintenance duration of component 2 respectively,

λ_1 and r_1 are the failure rate and repair time of component 1 respectively,

λ_2 and r_2 are the failure rate and repair time of component 2 respectively.

(b) Active failure of component 1 overlapping a maintenance outage of component 2

$$\begin{aligned}
\lambda_{am} &= \lambda_2''(\lambda_1^a r_2'') \\
r_{am} &= \frac{s_1 r_2''}{s_1 + r_2''} \\
U_{am} &= \lambda_{am} r_{am}
\end{aligned} \tag{3.6}$$

where,

λ_{am} is the failure rate of the overlapping failure event,

r_{am} is the outage time of the overlapping failure event,

U_{am} is the unavailability of the overlapping failure event,

λ_1^a and s_1 are the active failure rate and switching time of component 1 respectively,

λ_2'' and r_2'' are the maintenance rate and maintenance duration of component 2 respectively.

3.3 Station Component Reliability Data

Valid reliability data are essential in the performance of meaningful quantitative reliability evaluation. The data collected in most actual power systems is valuable and informative, but it usually cannot provide all the information required for adequacy assessment. The reliability data for station major components such as circuit breakers, bus bars and transformers used in this research work were obtained from several sources. The data for the circuit breakers and transformers in the RBTS were taken from [36]. The data for the circuit breakers and transformers in the IEEE-RTS were taken from [37]. The ratio of circuit breaker active failures to passive failures was derived from data shown in the CIGRE report (Working Group 06/ Study Committee 13: Reliability of HV Circuit Breakers) [38]. The bus bar data for the RBTS and IEEE-RTS were taken from [32] and [33] respectively. The station component maintenance outage data were taken from the RBTS [32].

RBTS reliability data

The basic reliability data for major station components, circuit breakers, bus bars and transformers, are as follows.

Circuit breaker

Active failure rate = 0.00963 failures per year

Passive failure rate = 0.00107 failures per year

Total failure rate＝0.0107 failures per year

Average outage duration = 93.62 hours

Switching time = 1 hour

Maintenance outage rate = 0.2 outages per year

Maintenance time = 108 hours

Bus bar

Failure rate = 0.025 failures per year

Outage duration = 10 hours

Station transformer

Failure rate = 0.02 failures per year

Outage duration = 768 hours

Maintenance outage rate = 0.2 failures per year

Maintenance time = 72 hours

Switching time = 1 hour

IEEE-RTS reliability data

The reliability data for breakers, bus bars and transformers are as follows.

Circuit breaker

138kV circuit breaker:

Active failure rate = 0.08271 failures per year

Passive failure rate = 0.00919 failures per year

Total failure rate＝0.0919 failures per year

Average outage duration = 172.70 hours

Switching time = 1 hour

Maintenance outage rate = 0.2 outages per year

Maintenance time = 108 hours

230kV circuit breaker:

Active failure rate = 0.11313 failures per year

Passive failure rate = 0.01257 failures per year

Total failure rate＝0.1257 failures per year

Average outage duration = 131.9 hours

Switching time = 1 hour

Maintenance outage rate = 0.2 outages per year

Maintenance time = 108 hours

Bus bar

138kV bus bar:

Failure rate = 0.027 failures per year

Outage duration = 19 hours

230kV bus bar:

Failure rate = 0.021 failures per year

Outage duration = 13 hours

Transformer

138kV transformer:

Failure rate = 0.158 f/yr

Outage duration = 181.26 hr

Switching time = 1 hour

Maintenance outage rate = 0.2 outages per year

Maintenance time = 72 hours

230kV transformer:

Failure rate = 0.1343 f/yr

Outage duration = 152.37 hrs

Switching time = 1 hour

Maintenance outage rate = 0.2 outages per year

Maintenance time = 72 hours

3.4 Basic Evaluation Procedures

The process used to incorporate station related outages can either be analytical or based on Monte Carlo simulation. An analytical method is applied in this thesis. This approach is relatively straightforward and can be applied to different station alternatives with reasonable accuracy.

The minimal cut set method [19] is used to incorporate station related outages in composite system reliability evaluation. A minimal cut set is a set of system components which, when failed, causes failure of the system but when any one component of the set has not failed, does not cause system failure. There are two kinds of minimal cut sets: independent minimal cut sets which cause the failure of only one terminal and common minimal cut sets which cause the failure of two or more terminals simultaneously. The reliability indices of the first group of minimal cut sets can be combined with those of the connected terminal. The reliability indices of the second group of minimal cut sets are treated as separate input data in composite system reliability evaluation.

The minimal cut set method is described and illustrated in the following using a ring bus station of the RBTS as an example. The voltage step-down transformer is not included in the reliability analysis and is usually associated directly with the customer load point performance.

3.4.1 Station Description

Figure 3.9 shows the single line diagram of Station 2 in the RBTS. This station contains seven generators, three transmission lines and one load point. The simplified station is expanded to the ring bus configuration shown in Figure 3.10, in which CB is the abbreviation for a circuit breaker. There are nine terminating elements on Bus 2 in Figures 3.9 and 3.10. The nine terminals in these figures are connected to transmission lines, transformers or loads.

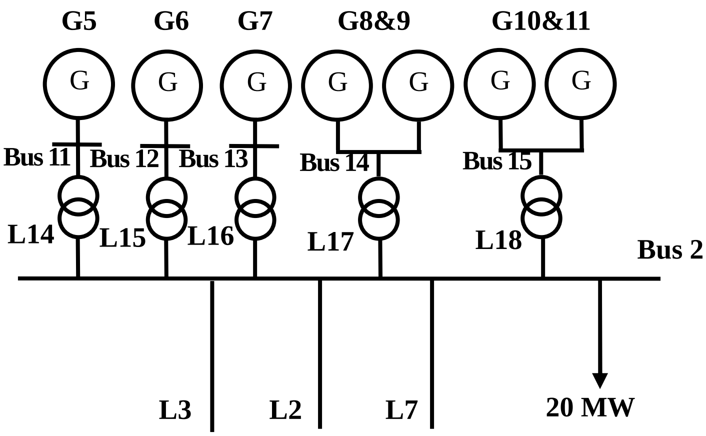

Figure 3.9: Single line diagram of Station 2 in the RBTS

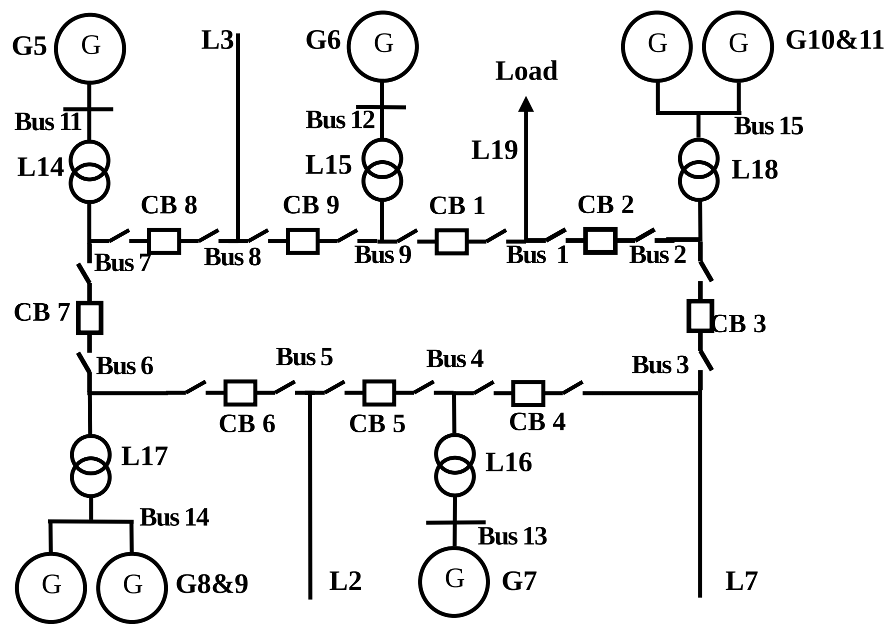

Figure 3.10: Single line diagram of ring bus Station 2 in the RBTS

3.4.2 Station Related Failure Events without Considering Scheduled Maintenance

The minimal cut sets for the nine terminals are shown in Table 3.1. The minimal cuts shown in Table 3.1 are used to illustrate the basic process. The total minimal cuts are divided into two groups, designated as common terminal minimal cuts and independent minimal cuts.

Table 3.1 shows that there are two common terminal minimal cut sets and nine independent minimal cut sets associated with transmission line L 2. In the first group, an active failure of CB5 results in the forced removal of both L 2 and L16 from service, similarly an active failure of CB6 results in the forced removal of both L 2 and L17. These failure events are designated as CB5 $(A)_6$ and CB6 $(A)_7$ in Table 3.1. Similar common minimal cuts exist for each terminal. The forced outage of Bus 5 is a first order independent minimal cut set and causes the removal of L 2. The line L 2 is also forced out of service when forced outages of CB5 and CB6 overlap. The remaining second order minimal cut sets are associated with overlapping failures of other elements. The nine independent minimal cut sets are designated as Set 7 in Table 3.1. The reliability indices for the two groups of cut sets can be calculated using the data and equations given earlier in this chapter.

3.4.3 Station Related Failure Events Related to Scheduled Maintenance

The minimal cut sets associated with station maintenance outages are shown in Table 3.2 using L 2 as the example. There are six independent minimal cut sets but no common terminal minimal cut sets. The six independent cut sets for L 2 are designated as Set 16 in Table 3.2. The terminal L 2 is removed from service when a maintenance outage of CB5 is overlapped by a forced outage of CB6, a forced outage of Bus 6 or by an active failure of CB7. Three similar minimal cuts exist associated with the maintenance (CB6 (M)) of CB6. When a component is removed for maintenance, the system configuration is in weakened condition and is vulnerable to additional element failures. The reliability indices for these failure events can be evaluated using the equations and data introduced earlier in this chapter.

Table 3.1: Station terminal minimal cut sets (without considering station related maintenance outages)

Minimal cut sets type	L 14 (Transformer)	L 15 (Transformer)	L 16 (Transformer)	L 17 (Transformer)	L 18 (Transformer)
Common minimal cut sets	CB7 (A) $_{1}$	CB1 (A) $_{3}$	CB4 (A) $_{5}$	CB6 (A) $_{7}$	CB2 (A) $_{8}$
	CB8 (A) $_{2}$	CB9 (A) $_{4}$	CB5 (A) $_{6}$	CB7 (A) $_{1}$	CB3 (A) $_{9}$
	CB6+CB8 $_{10}$ *	-	-	CB6+CB8 $_{10}$ *	-
Independent minimal cut sets	Bus7	Bus9	Bus4	Bus6	Bus2
	CB7(T)+CB8(T)	CB1(T)+CB9(T)	CB4(T)+CB5(T)	CB6(T)+CB7(T)	CB2(T)+CB3(T)
	CB7(T)+Bus8	CB1(T)+Bus8	CB4(T)+Bus5	CB6(T)+Bus7	CB2(T)+Bus3
	CB8(T)+Bus6	CB9(T)+Bus1	CB5(T)+Bus3	CB7(T)+Bus5	CB3(T)+Bus1
	CB7(T)+ CB9(A)	CB1(T)+ CB8(A)	CB4(T)+ CB6(A)	CB6(T)+ CB8(A)	CB2(T)+ CB4(A)
	CB8(T)+ CB6(A)	CB9(T)+ CB2(A)	CB5(T)+ CB3(A)	CB7(T)+ CB5(A)	CB3(T)+ CB1(A)
	CB6(A)+Bus8	CB2(A)+Bus8	CB3(A)+Bus5	CB5(A)+Bus7	CB1(A)+Bus3
	CB9(A)+Bus6	CB8(A)+Bus1	CB6(A)+Bus3	CB8(A)+Bus5	CB4(A)+Bus1
	Bus6+Bus8	Bus1+Bus8	Bus3+Bus5	Bus5+Bus7	Bus1+Bus3
Cut set group name	Set 1	Set 2	Set 3	Set 4	Set 5

Minimal cut sets type	L 19 (Load point)	L 2 (line)	L 3 (line)	L 7 (line)
Common minimal cut sets	CB1 (A) $_{3}$	CB5 (A) $_{6}$	CB8 (A) $_{2}$	CB3 (A) $_{9}$
	CB2 (A) $_{8}$	CB6 (A) $_{7}$	CB9 (A) $_{4}$	CB4 (A) $_{5}$
Independent minimal cut sets	Bus1	Bus5	Bus8	Bus3
	CB1(T)+CB2(T)	CB5(T)+CB6(T)	CB8(T)+CB9(T)	CB3(T)+CB4(T)
	CB1(T)+Bus2	CB5(T)+Bus6	CB8(T)+Bus9	CB3(T)+Bus4
	CB2(T)+Bus9	CB6(T)+Bus4	CB9(T)+Bus7	CB4(T)+Bus2
	CB1(T)+ CB3(A)	CB5(T)+ CB7(A)	CB8(T)+ CB1(A)	CB3(T)+ CB5(A)
	CB2(T)+ CB9(A)	CB6(T)+ CB4(A)	CB9(T)+ CB7(A)	CB4(T)+ CB2(A)
	CB9(A)+Bus2	CB4(A)+Bus6	CB7(A)+Bus9	CB2(A)+Bus4
	CB3(A)+Bus9	CB7(A)+Bus4	CB1(A)+Bus7	CB5(A)+Bus2
	Bus2+Bus9	Bus4+Bus6	Bus7+Bus9	Bus2+Bus4
Cut set group name	Set 6	Set 7	Set 8	Set 9

* Other 2nd order cuts exist, but are neglected.

Where A represents a circuit breaker active failure and T represents a circuit breaker total failure.

Table 3.2: Station terminal minimal cut sets (station maintenance outages)

Minimal cut sets type	L 14 (Transformer)	L 15 (Transformer)	L 16 (Transformer)	L 17 (Transformer)	L 18 (Transformer)
Independent minimal cut sets for maintenance outages	CB7(M)+CB8(T)	CB1(M)+CB9(T)	CB4(M)+CB5(T)	CB6(M)+CB7(T)	CB2(M)+CB3(T)
	CB8(M)+CB7(T)	CB9(M)+CB1(T)	CB5(M)+CB4(T)	CB7(M)+CB6(T)	CB3(M)+CB2(T)
	CB7(M)+Bus8	CB1(M)+Bus8	CB4(M)+Bus5	CB6(M)+Bus7	CB2(M)+Bus3
	CB8(M)+Bus6	CB9(M)+Bus1	CB5(M)+Bus3	CB7(M)+Bus5	CB3(M)+Bus1
	CB7(M)+ CB9(A)	CB1(M)+ CB8(A)	CB4(M)+ CB6(A)	CB6(M)+ CB8(A)	CB2(M)+ CB4(A)
	CB8(M)+ CB6(A)	CB9(M)+ CB2(A)	CB5(M)+ CB3(A)	CB7(M)+ CB5(A)	CB3(M)+ CB1(A)
Cut set group name	Set 10	Set 11	Set 12	Set 13	Set 14
Minimal cut sets type	**L 19 (Load point)**	**L 2 (line)**	**L 3 (line)**	**L 7 (line)**	
Independent minimal cut sets for maintenance outages	CB1(M)+CB2(T)	CB5(M)+CB6(T)	CB8(M)+CB9(T)	CB3(M)+CB4(T)	
	CB2(M)+CB2(T)	CB6(M)+CB5(T)	CB9(M)+CB8(T)	CB4(M)+CB3(T)	
	CB1(M)+Bus2	CB5(M)+Bus6	CB8(M)+Bus9	CB3(M)+Bus4	
	CB2(M)+Bus9	CB6(M)+Bus4	CB9(M)+Bus7	CB4(M)+Bus2	
	CB1(M)+ CB3(A)	CB5(M)+ CB7(A)	CB8(M)+ CB1(A)	CB3(M)+ CB5(A)	
	CB2(M)+ CB9(A)	CB6(M)+ CB4(A)	CB9(M)+ CB7(A)	CB4(M)+ CB2(A)	
Cut set group name	Set 15	Set 16	Set 17	Set 18	

Where,

M represents a circuit breaker maintenance outage.

3.4.4 Applications

The minimal cut set technique is illustrated by application to Station 2 of the RBTS in Tables 3.1 and 3.2. The circuit breaker, bus bar and transformer reliability data are given in Section 3.3. The aggregated reliability parameters for the common terminal minimal cut sets and the independent minimal cut sets for L 2 can be calculated using the equations presented earlier and Equation 3.7, and are shown in Tables 3.3 and 3.4 respectively.

$$\begin{aligned} \lambda_{seti} &= \sum_{k=1}^{n} \lambda_k \\ U_{seti} &= \sum_{k=1}^{n} U_k \\ r_{seti} &= \frac{U_{seti}}{\lambda_{seti}} \end{aligned} \tag{3.7}$$

where,

λ_k is the failure rate of the *k*th independent minimal cut set in Set *i*,

U_k is the unavailability of the *k*th independent minimal cut set in Set *i*,

λ_{seti} is the total failure rate of Set *i*,

U_{seti} is the total unavailability of Set *i*,

r_{seti} is the average repair time of Set *i*.

The reliability indices of the common terminal minimal cut sets for Line 2 are shown in Table 3.3. Circuit breaker active failures result in relatively higher unavailability in comparison with other kinds of failure event and therefore cannot be ignored. These parameters are treated as separate input data in composite system reliability evaluation.

Table 3.4 shows the reliability indices of the independent minimal cut sets for Line 2. It can be seen that the failure rate and unavailability of Set 7 are larger than those of Set 16 which is related to station maintenance outages.

Table 3.3: Common terminal minimal cut sets for Line 2

Failure events	Failure rate (f/yr)	Repair time (hr)	Unavailability (hr/yr)
Forced outages			
CB5 (A) $_7$	0.009630	1	0.009630
CB6 (A) $_8$	0.009630	1	0.009630

Table 3.4: Independent minimal cut sets for Line 2

Failure events	Failure rate (f/yr)	Repair time (hr)	Unavailability (hr/yr)
Forced outages			
Bus5	0.025	10	0.25
CB5(T)+CB6(T)	0.000002	46.810000	0.000115
CB5(T)+Bus6	0.000003	9.034935	0.000029
CB6(T)+Bus4	0.000003	9.034935	0.000029
CB5(T)+ CB7(A)	0.000001	0.989431	0.000001
CB6(T)+ CB4(A)	0.000001	0.989431	0.000001
CB4(A)+Bus6	0.000000	0.909091	0.000000
CB7(A)+Bus4	0.000000	0.909091	0.000000
Bus4+Bus6	0.000001	5.000000	0.000007
Subtotal for Set 7	0.025013	10.002050	0.250182
Maintenance outages			
CB5(M)+CB6(T)	0.000026	50.148596	0.001323
CB6(M)+CB5(T)	0.000026	50.148596	0.001323
CB5(M)+Bus6	0.000062	9.152542	0.000564
CB6(M)+Bus4	0.000062	9.152542	0.000564
CB5(M)+ CB7(A)	0.000024	0.990826	0.000024
CB6(M)+ CB4(A)	0.000024	0.990826	0.000024
Subtotal for Set 16	0.000224	17.095636	0.003822
Total	0.025237	10.064885	0.254003

3.4.5 Modified System Component Reliability Data

The modified reliability data for the nine terminals including the effects of station maintenance outages can be obtained by aggregating the data from all the independent minimal cut sets. The required equations including the station maintenance outages for each terminal element are as follows.

$$\begin{aligned} \lambda' &= \lambda + \lambda_{seta} + \lambda_{setb} \\ U' &= U + U_{seta} + U_{setb} \\ r' &= \frac{U'}{\lambda'} \end{aligned} \tag{3.8}$$

Where,

λ' is the modified failure rate of the terminal element,

U' is the modified unavailability of the terminal element,

r' is the modified average outage time of the terminal element,

λ is the original failure rate of the terminal element, U is the original unavailability of the terminal element,

λ_{seta} is the total failure rate of Set a (which does not include station maintenance outages),

λ_{setb} is the total failure rate of Set b (due to station maintenance outages),

U_{seta} is the total unavailability of Set a,

U_{setb} is the total unavailability of Set b.

As an example, the modified reliability data of Line 2 can be obtained using Equation 3.8. Line 2 is connected to Stations 2 and 4 and therefore the reliability data of Line 2 should be modified by aggregating the associated independent minimal cut sets in both stations. The values for Station 2 are shown in Table 3.3. The relevant equations are as follows.

$$
\begin{aligned}
\lambda_{seta} &= \lambda_{set7} + \lambda_{set7}' \\
\lambda_{setb} &= \lambda_{set16} + \lambda_{set16}' \\
U_{seta} &= U_{set7} + U_{set7}' \\
U_{setb} &= U_{set16} + U_{set16}'
\end{aligned}
\tag{3.9}
$$

Where,

λ_{set7} is the failure rate of the station related forced outages in Station 2,

λ_{set7}' is the failure rate of the relevant station related forced outages in Station 4,

λ_{set16} is the failure rate of the station related maintenance outages in Station 2,

λ_{set16}' is the failure rate of the relevant station related maintenance outages in Station 4,

U_{set7} is the unavailability of the station related forced outages in Station 2,

U_{set7}' is the unavailability of the relevant station related forced outages in Station 4,

U_{set16} is the unavailability of the station related maintenance outages in Station 2,

U_{set16}' is the unavailability of the relevant station related maintenance outages in Station 4,

Equations 3.8 and 3.9 are used to modify the reliability data for each terminal element.

3.5 Summary

This chapter describes the evaluation technique used to incorporate station related forced and maintenance outages in composite system reliability evaluation. The state space models for the individual station components and the relevant equations are presented. The minimal cut set method is used to incorporate station related forced and maintenance outages in composite system reliability evaluation.

The objective of the station evaluation technique presented in this chapter is to incorporate the related station equipment failure parameters in the reliability parameters of the connected terminal components. The reliability parameters of the independent minimal cuts are added directly to the terminal element parameters. The common terminal minimal cuts are considered as common mode failures and their parameters are incorporated directly as input data in MECORE.

The evaluation technique is illustrated and applied using a ring bus station of the RBTS as an example. The results show that the connected element failure rate and unavailability due to station related forced outages are larger than those due to station related maintenance outages. The reliability of all the connected elements decreases slightly after station related maintenance outages are included. The impact on composite system reliability performance of incorporating station related maintenance outages is illustrated by application to the RBTS and the IEEE-RTS in the next chapter.

Chapter 4

Application of Station Related Maintenance Outages in Composite System Reliability Evaluation

4.1 Introduction

Maintenance is continually performed in an electric power system in order to keep equipment in good working condition and to prolong their useful life. Preventive maintenance is considered to be essential for ensuring high component and system reliability. Failures of other station components while maintenance is being performed, however, can cause the forced removal of one or more connected electric circuits from service and can have considerable impact on the ability of the station to perform its assigned function. Proper functioning of station equipment is important and essential in the provision of reliability and quality of power supply in a bulk power system. The objective of this chapter is to illustrate the effects of station related maintenance outages on composite system reliability evaluation.

Preventive maintenance programs are implemented in switching stations and substations to increase the mean time to failure of the equipment. In the past, maintenance policies were often planned and coordinated centrally by electric utilities and power pools to minimize disruption to customers. Maintenance was usually done during low-load seasons and the timing was affected by such considerations as system risk and production costs. In a deregulated scenario, maintenance is often scheduled by individual companies that own and operate generating units and transmission facilities. Under such circumstances the decision when to maintain a station component such as a circuit breaker, bus bar or transformer is driven by profit incentives rather than by the optimal system cost of maintenance and repair. Probabilistic models, equations and station component reliability data including maintenance outages are presented in Chapter 3. These techniques are used in this chapter to evaluate the effects of station related maintenance outages on the reliability of the RBTS and the IEEE-RTS.

Station configurations are designed to interconnect energy sources, transmission facilities and load points. The physical configuration of a station directly affects the reliability of power supply to the connected load points and a major issue in bulk system planning and design is to minimize the impacts of station related outages. This chapter illustrates the effects of station related forced and maintenance outages in the RBTS and IEEE-RTS due to different station configurations. The system reliability performances are compared using the reliability indices shown in Chapter 2 for the different station configurations. The stations used in the RBTS analyses are ring bus, double bus double breaker, one and one half breaker and one and one third breaker configurations. The stations used in the IEEE-RTS studies are ring bus, and mixed ring bus and one and one half breaker configurations.

4.2 RBTS Analysis

Station configurations directly impact the reliability of the power supply to the load points. It is relatively difficult to evaluate and compare the reliability performance of a large composite system with different station configurations. The RBTS is a small composite system and can be easily used to conduct a comparison. The evaluation technique introduced in the last chapter is applied to incorporate station related maintenance outages in the RBTS using the four different station configurations. The reliability data for the station equipment are given in Section 3.3.

Figure 4.1 shows the extended single line diagram of the RBTS incorporating station related outages. This diagram is very similar to that shown in Figure 2.3. The data for the connected terminal components in Figure 4.1 are modified to include the station related effects.

A series of reliability studies were conducted in the RBTS using the four station configurations. The reliability data of the system components were modified to include the effects of station related outages and MECORE was used to evaluate the system reliability performance for the different station configurations. The modified generator

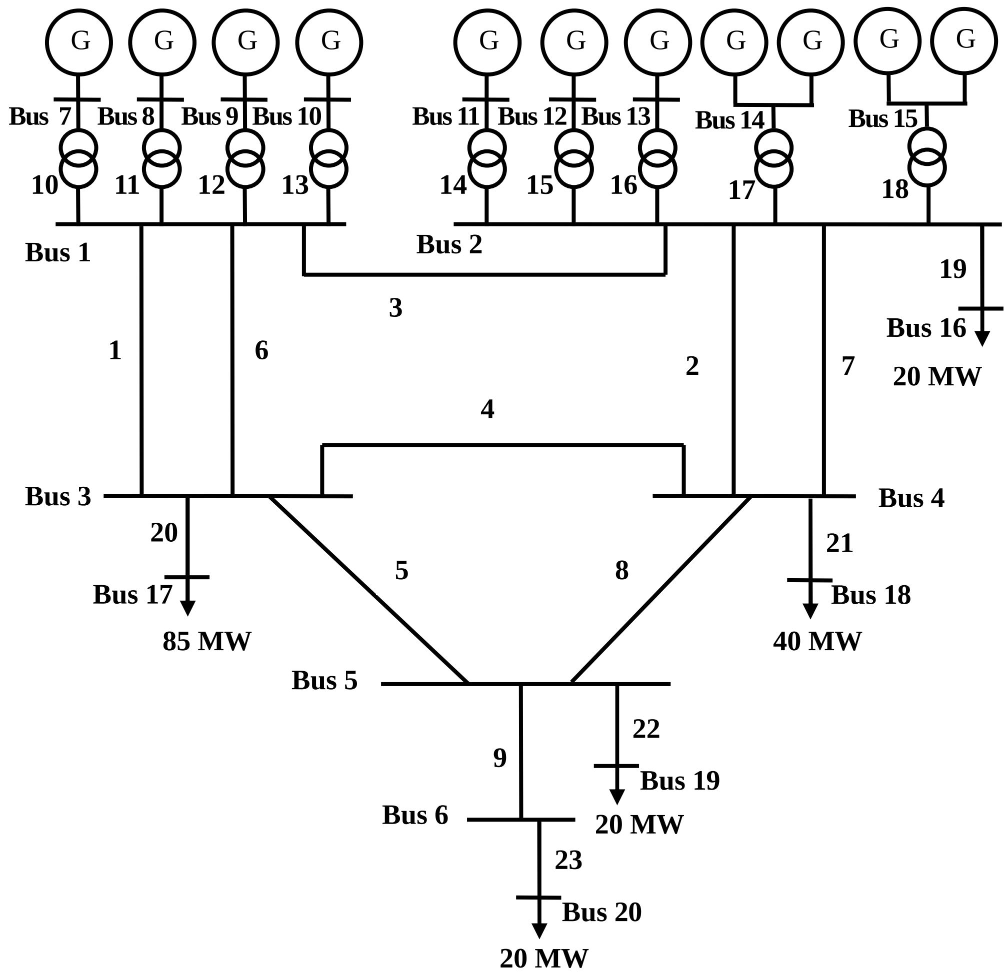

Figure 4.1: Extended single line diagram of the RBTS including station related outages

data for the RBTS with generating unit transformers are given in Table A.10. The relevant reliability data of the transmission lines, transformers and equivalent load circuits for the RBTS with the four different station schemes are shown in Appendices B and C.

The single line diagrams for the RBTS with ring bus, double bus double breaker, one and one half breaker and one and one third breaker schemes are shown in Figures 4.2 – 4.5 respectively [28]. The modified generator data are given in Table A.10. The modified reliability data for the transmission lines, transformers and equivalent load circuits for the RBTS with the four different station schemes, without and with station maintenance outages are shown in Tables B.1-B.8 respectively. The load point and system reliability indices for the RBTS with the four different station configurations are evaluated using these data and shown in the following.

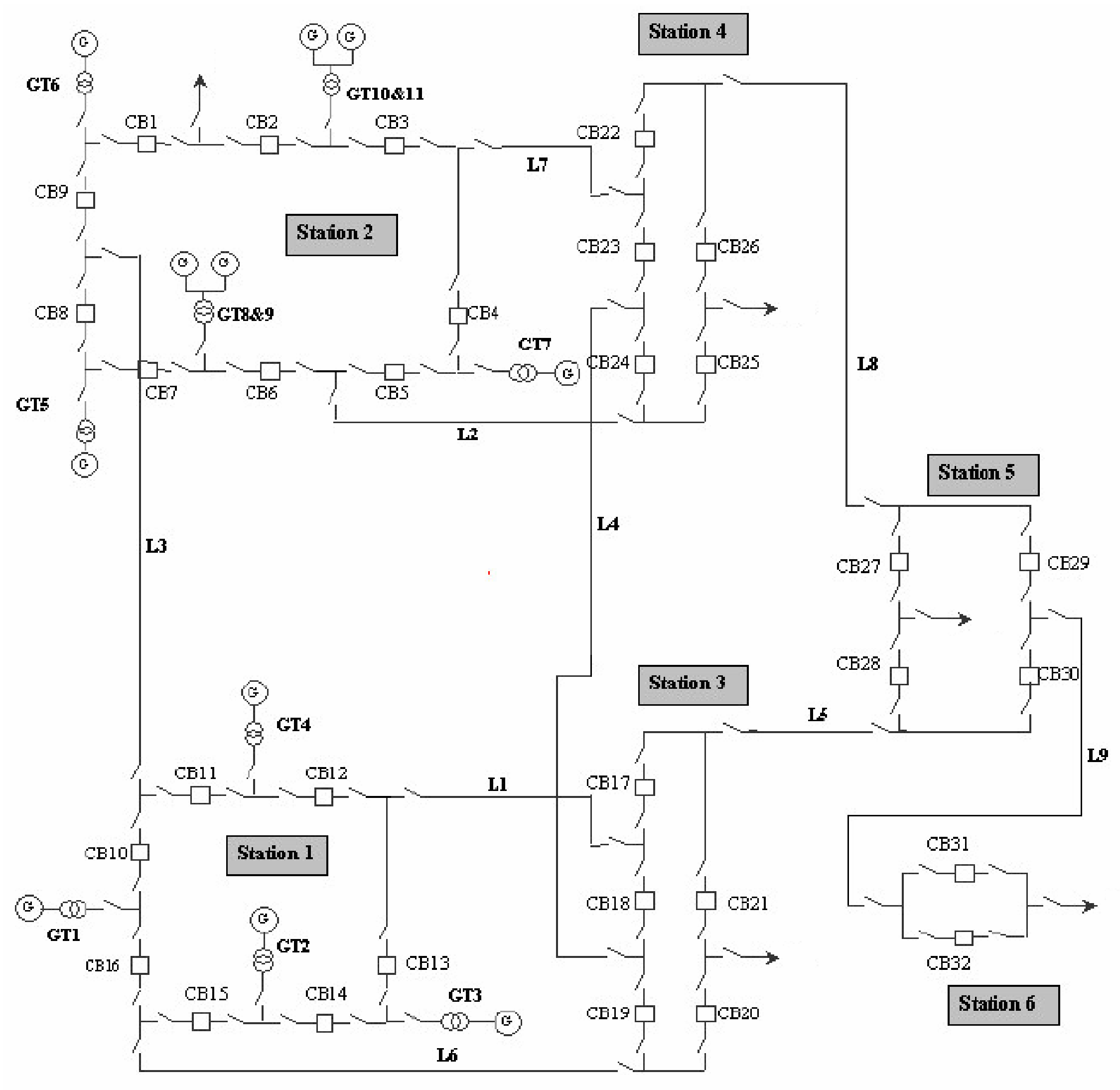

Figure 4.2: Single line diagram of the RBTS with ring bus schemes

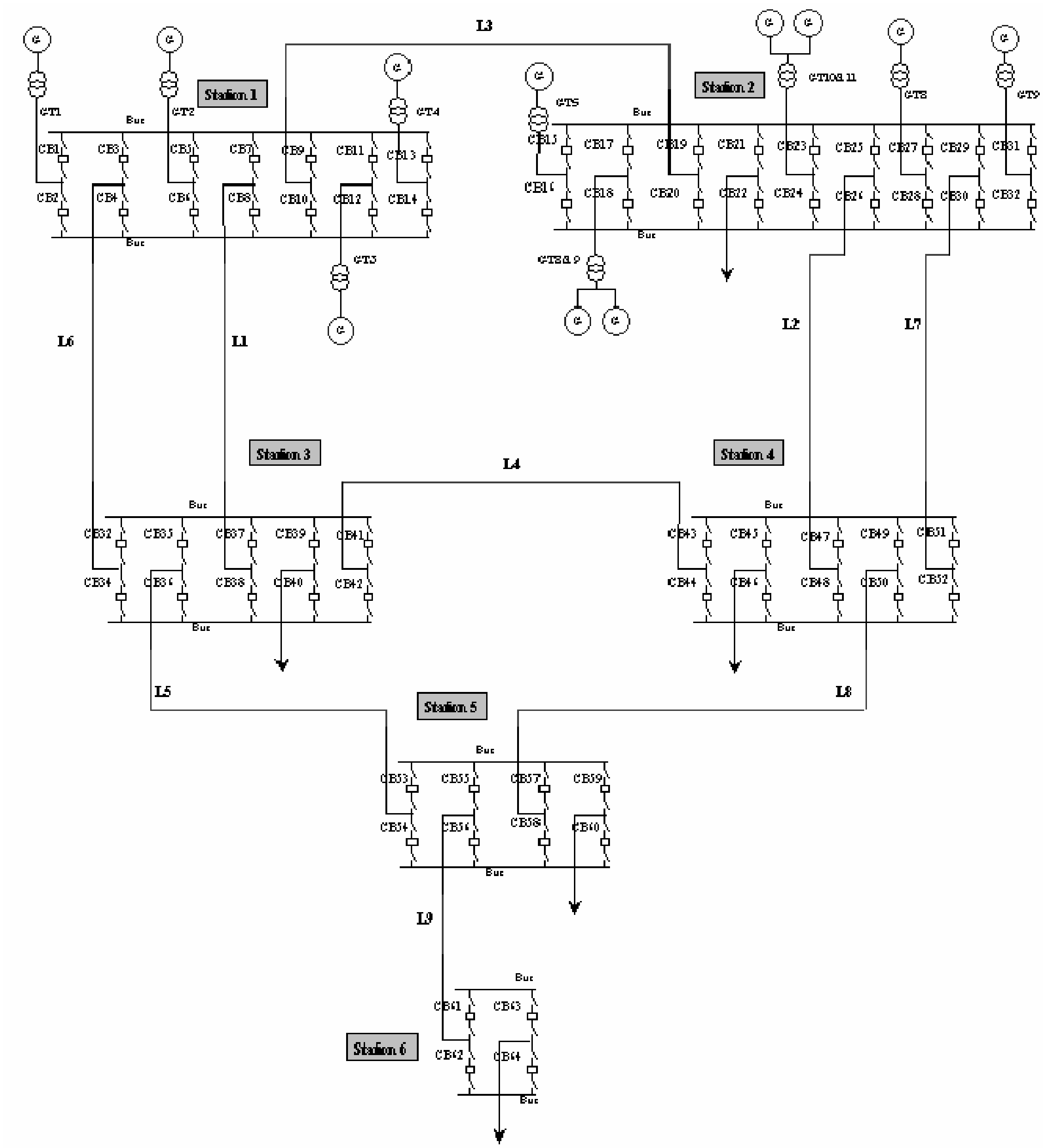

Figure 4.3: Single line diagram of the RBTS with double bus double breaker schemes

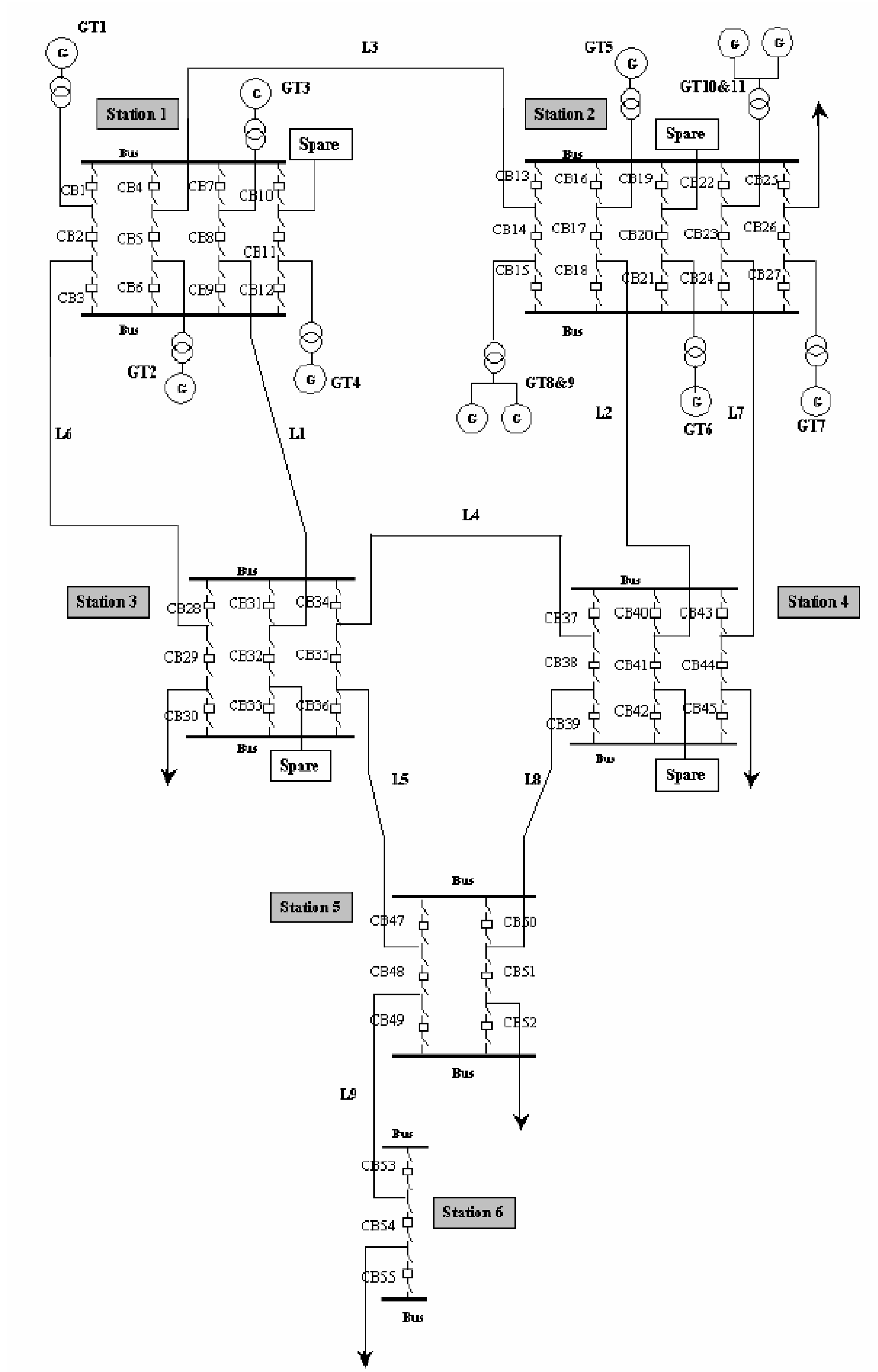

Figure 4.4: Single line diagram of the RBTS with one and one half breaker schemes

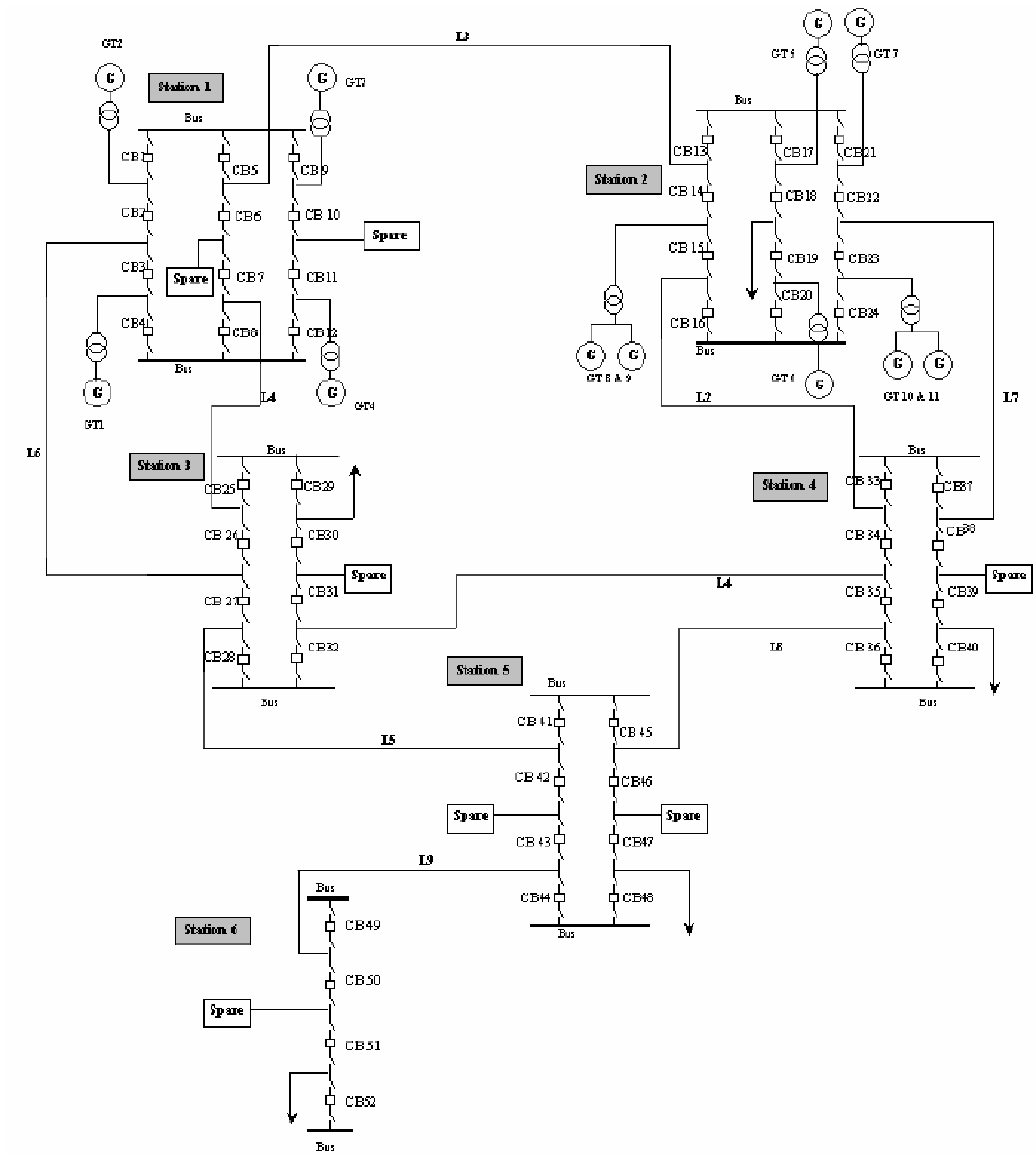

Figure 4.5: Single line diagram of the RBTS with one and one third breaker schemes

RBTS with ring bus configurations

The annual load point and system indices for the RBTS without and with maintenance outages are shown in Tables 4.1 and 4.2. It can be seen that the load point and system indices increase significantly due to including station related forced outages by comparing the results in Tables 4.1 and 4.2 with those in Tables 2.11 and 2.12 in Chapter 2. The reliability indices increase slightly by including station maintenance outages. The major contribution to the increase in the system EENS is from the load point EENS at Bus 17 (Station 3).

Table 4.1: Annual load point indices of the RBTS with ring bus schemes

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr) (Without mainte.)	EENS (MWh/yr) (Maintenance)
16	0.00003	0.11467	1.467	0.00033	2.914	2.914
17	0.00022	0.21148	5.028	0.00368	32.212	37.249
18	0.00003	0.10198	2.590	0.00087	7.651	7.663
19	0.00004	0.14124	1.790	0.00047	4.155	4.185
20	0.00130	2.13507	27.135	0.01650	144.570	144.881

Table 4.2: Annual system indices of the RBTS with ring bus schemes

Annual Indices	Without mainte.	Maintenance
ENLC (1/yr)	2.65752	3.16304
ADLC (hrs/disturbance)	5.32	4.61
EDLC (hrs/yr)	14.13	14.57
PLC	0.00161	0.00166
EDNS (MW)	0.022	0.022
EENS (MWh/yr)	191.502	196.893
EDC (k$/yr)	846.44	870.27
BPII (MW/MW-yr)	0.20546	0.24112
BPECI (MWh/MW-yr)	1.035	1.064
BPACI (MW/disturbance)	14.303	14.102
MBECI (MW/MW)	0.00012	0.00012
SI (system minutes/yr)	62.11	63.86

RBTS with double bus double breaker configurations

The annual load point and system indices for the RBTS with double bus double breaker stations, without and with station related maintenance outages are shown in Tables 4.3 and 4.4. It can be seen that the load point and system indices increase due to incorporating station related outages by comparing these results with those shown in Tables 2.11 and 2.12. It also shows that incorporating station maintenance outages affects the load point and system reliability indices.

Table 4.3: Annual load point indices of the RBTS with double bus double breaker schemes

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr) (Without mainte.)	EENS (MWh/yr) (Maintenance)
16	0.00000	0.03135	0401	0.00004	0.392	0.448
17	0.00020	0.12101	1.955	0.00220	19.301	24.311
18	0.00000	0.00987	0.233	0.00003	0.255	0.716
19	0.00001	0.02315	0.285	0.00006	0.513	0.599
20	0.00121	1.25323	15.910	0.01539	134.838	135.038

Table 4.4: Annual system indices of the RBTS with double bus double breaker schemes

Annual Indices	Without mainte.	Maintenance
ENLC (1/yr)	1.42700	1.46343
ADLC (hrs/disturbance)	8.65	8.75
EDLC (hrs/yr)	12.35	12.81
PLC	0.00141	0.00146
EDNS (MW)	0.018	0.018
EENS (MWh/yr)	155.300	161.113
EDC (k$/yr)	686.42	712.12
BPII (MW/MW-yr)	0.10164	0.10457
BPECI (MWh/MW-yr)	0.839	0.871
BPACI (MW/disturbance)	13.163	13.219
MBECI (MW/MW)	0.00010	0.00010
SI (system minutes/yr)	50.37	52.25

RBTS with one and one half breaker configurations

The annual load point indices and system indices for the RBTS with one and one half breaker stations are shown in Tables 4.5 and 4.6. It can be seen that the load point and system indices for the RBTS with one and one half breaker stations are higher than those for the RBTS with double bus double breaker stations but lower than those for the RBTS with ring bus stations. It also shows the effects of station related maintenance outages on the load point and system reliability of the RBTS.

Table 4.5: Annual load point indices of the RBTS with one and one half breaker schemes

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr) (Without mainte.)	EENS (MWh/yr) (Maintenance)
16	0.00000	0.02358	0.302	0.00003	0.224	0.224
17	0.00020	0.13720	2.154	0.00220	19.299	24.785
18	0.00000	0.00758	0.175	0.00002	0.143	0.379
19	0.00000	0.03931	0.489	0.00005	0.457	0.599
20	0.00133	1.56806	19.918	0.01684	147.504	147.590

Table 4.6: Annual system indices of the RBTS with one and one half breaker schemes

Annual Indices	Without mainte.	Maintenance
ENLC (1/yr)	1.74933	2.00383
ADLC (hrs/disturbance)	7.61	6.87
EDLC (hrs/yr)	13.32	13.77
PLC	0.00152	0.00157
EDNS (MW)	0.019	0.020
EENS (MWh/yr)	167.627	173.578
EDC (k$/yr)	740.91	767.22
BPII (MW/MW-yr)	0.12453	0.14304
BPECI (MWh/MW-yr)	0.906	0.938
BPACI (MW/disturbance)	13.170	13.206
MBECI (MW/MW)	0.00010	0.00011
SI (system minutes/yr)	54.37	56.30

RBTS with one and one third breaker configurations

The annual load point indices and system indices for the RBTS with one and one third breaker stations are shown in Tables 4.7 and 4.8. It can be seen that the load point and system indices for the RBTS with one and one third breaker stations are higher than those for the RBTS with one and one half breaker stations, while lower than those for the RBTS with ring bus stations. It also shows that station related maintenance outages have a relatively small effect on the composite system reliability.

Table 4.7: Annual load point indices of the RBTS with one and one third breaker schemes

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr) (Without mainte.)	EENS (MWh/yr) (Maintenance)
16	0.00000	0.02426	0.310	0.00001	0.112	0.224
17	0.00020	0.13768	2.103	0.00221	19.322	25.047
18	0.00000	0.00972	0.230	0.00003	0.255	0.828
19	0.00001	0.05099	0.636	0.00006	0.513	0.767
20	0.00143	1.77348	22.512	0.01823	159.663	159.804

Table 4.8: Annual system indices of the RBTS with one and one third breaker schemes

Annual Indices	Without mainte.	Maintenance
ENLC (1/yr)	1.96413	2.31851
ADLC (hrs/disturbance)	7.26	6.37
EDLC (hrs/yr)	14.27	14.76
PLC	0.00163	0.00168
EDNS (MW)	0.021	0.021
EENS (MWh/yr)	179.865	186.670
EDC (k$/yr)	795.00	825.08
BPII (MW/MW-yr)	0.13941	0.16672

Table 4.8: (Continued)

Annual Indices	Without mainte.	Maintenance
BPECI (MWh/MW-yr)	0.972	1.009
BPACI (MW/disturbance)	13.131	13.303
MBECI (MW/MW)	0.00011	0.00012
SI (system minutes/yr)	58.33	60.54

Comparison of the RBTS with the four different station configurations

Comparisons of the increases in the annual system indices for the RBTS with the four different station schemes, without and with station maintenance outages are shown in Figures 4.6 and 4.7 respectively. As noted earlier, the base case reliability indices for the RBTS without incorporating station related outages are shown in Tables 2.11 and 2.12.

Comparing the EENS and SI indices in Figures 4.6 and 4.7, the RBTS with double bus double breaker stations has the lowest values and is the most reliable system, the RBTS with one and one half breaker stations is the second most reliable system, the one and one third breaker stations provide the third most reliable system, and the RBTS with ring bus stations is the least reliable. Double bus double breaker station configurations, however, are the most expensive schemes and require the most equipment.

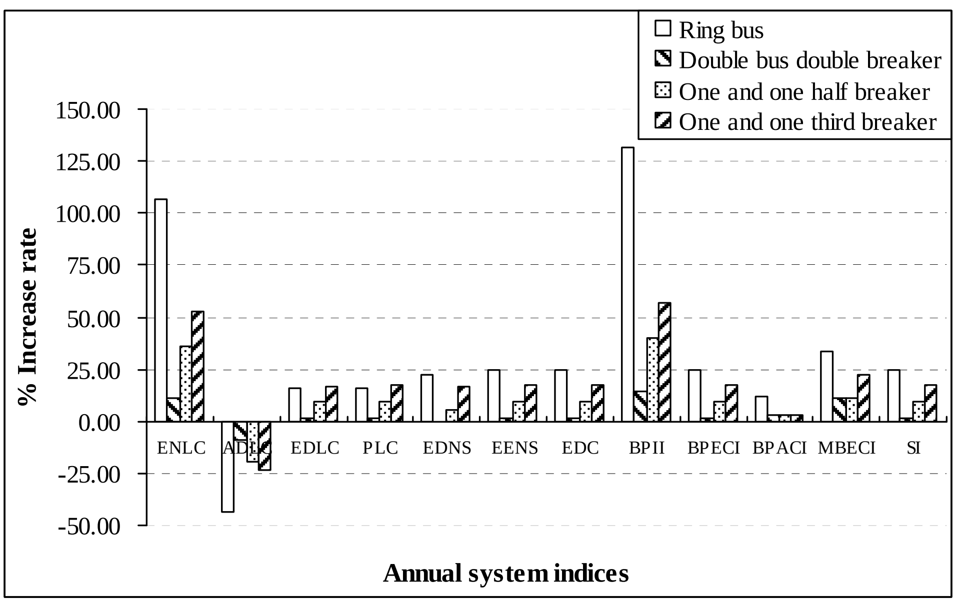

Figure 4.6: System reliability comparison for the RBTS with the four different station configurations (without station maintenance outages)

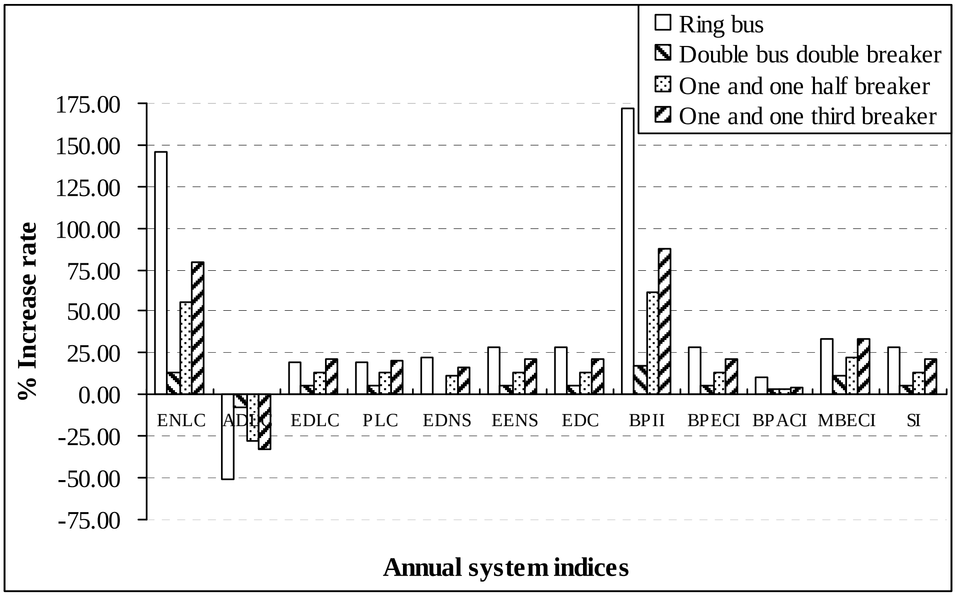

Figure 4.7: System reliability comparison for the RBTS with the four different station configurations (considering station maintenance outages)

The results show that station related maintenance outages have relatively small impacts on the RBTS with the four different station schemes. The reliability indices of the load point at Station 3 provide the major contribution to the increase in the system indices.

The load point EENS at Station 6 is the major contribution to the system EENS whether maintenance outages are included or not because it is supplied by a radial transmission line. The RBTS was therefore modified in the next section in order to focus on the effects of station related maintenance outages.

4.3 The Modified RBTS Analysis

The load point and system reliability indices are dominated by the Station 6 values due to the radial line supply to this bus. The original RBTS was modified by removing the radial line supplying Bus 6 and including this load at Bus 5 in order to focus on the effects of station related maintenance outages. Figure 4.8 shows the single line diagram of the system studied. The reliability data for the station components are given in Section 3.3.

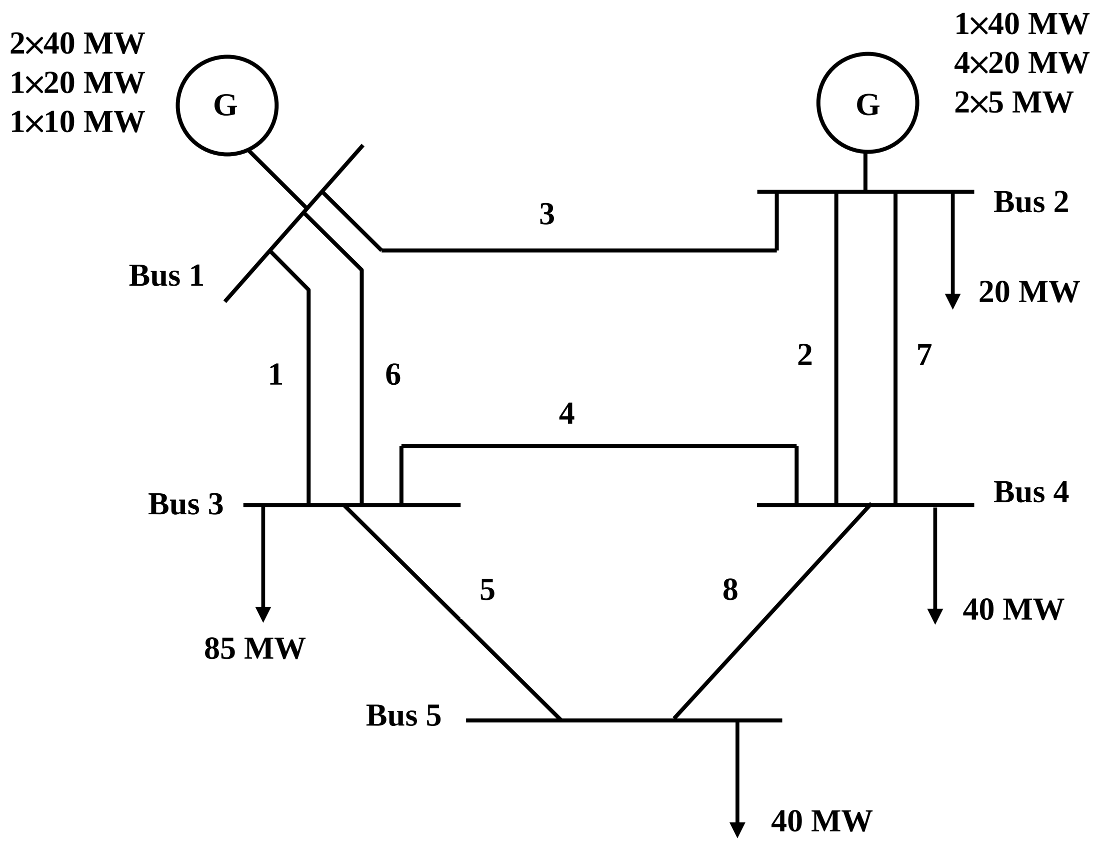

Figure 4.8: Single line diagram of the modified RBTS

4.3.1 The Modified RBTS Base Case Analysis

The modified RBTS with generating unit transformers are shown in Figure 4.9. The annual indices for the load bus and the overall system of the modified RBTS with generating unit transformers are shown in Tables 4.9 and 4.10 and used as base case results.

Table 4.9: Annual load point indices of the modified RBTS (base case)

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)
2	0.00000	0.00000	0.000	0.00000	0.000
3	0.00020	0.10812	1.244	0.00217	19.036
4	0.00000	0.00105	0.008	0.00000	0.034
5	0.00001	0.00865	0.133	0.00008	0.743

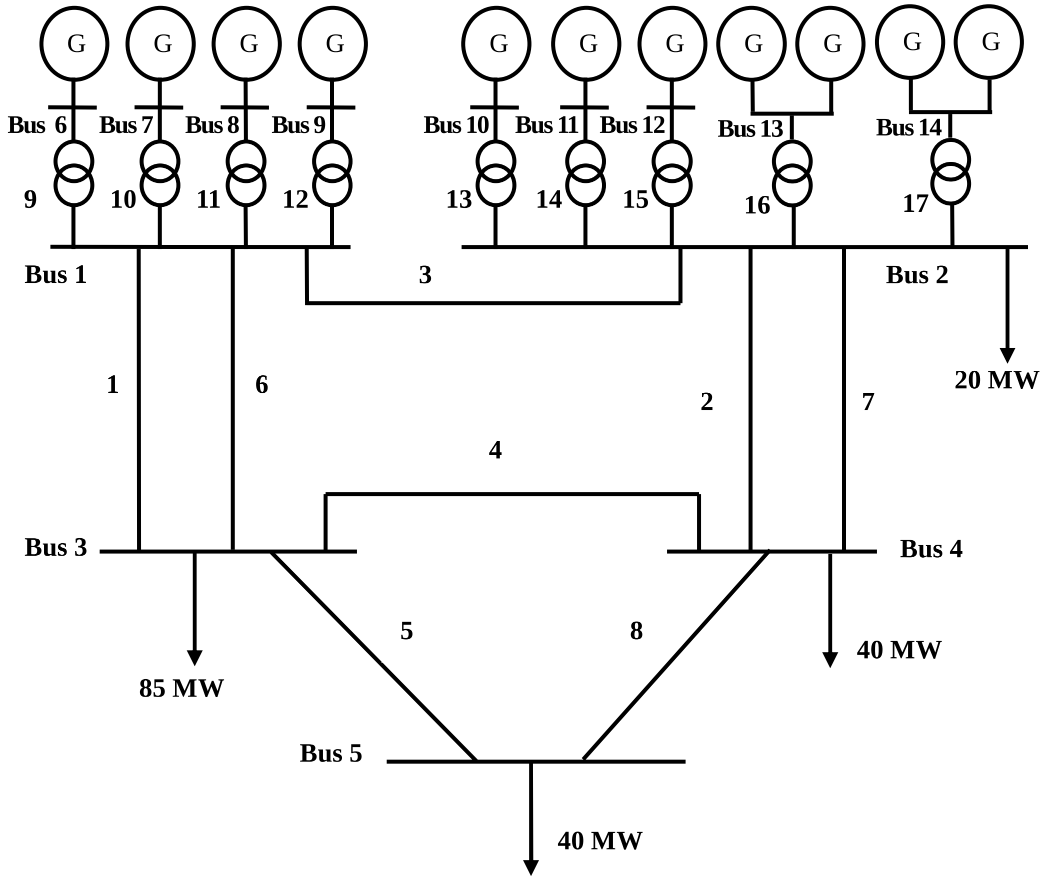

Figure 4.9: Extended single line diagram of the modified RBTS including station related outages

Table 4.10: Annual system indices of the modified RBTS (base case)

Indices	Values
ENLC (1/yr)	0.11185
ADLC (hrs/disturbance)	15.63
EDLC (hrs/yr)	1.748
PLC	0.00020
EDNS (MW)	0.002
EENS (MWh/yr)	19.813
EDC (k$/yr)	87.576
BPII (MW/MW-yr)	0.00749
BPECI (MWh/MW-yr)	0.107
BPACI (MW/disturbance)	12.384
MBECI (MW/MW)	0.00001
SI (system minutes/yr)	6.43

4.3.2 Reliability Analysis for the Modified RBTS with the Four Station Configurations

The extended single line diagram of the modified RBTS including station related outages is shown in Figure 4.10. The data for the connected terminal components in Figure 4.10 are modified to incorporate the station related effects. The single line diagrams for the modified RBTS with ring bus, double bus double breaker, one and one half breaker and one and one third breaker schemes are shown in Figures 4.11 – 4.14 respectively [28]. The modified generator data are given in Table A.11. The reliability data of the transmission lines, transformers and equivalent load circuits for the modified RBTS with the four different station schemes and without and with station maintenance outages are shown in Tables C.1-C.8 respectively. The load point and system reliability indices for the RBTS with the four different station configurations are shown in Tables 4.11 to 4.22.

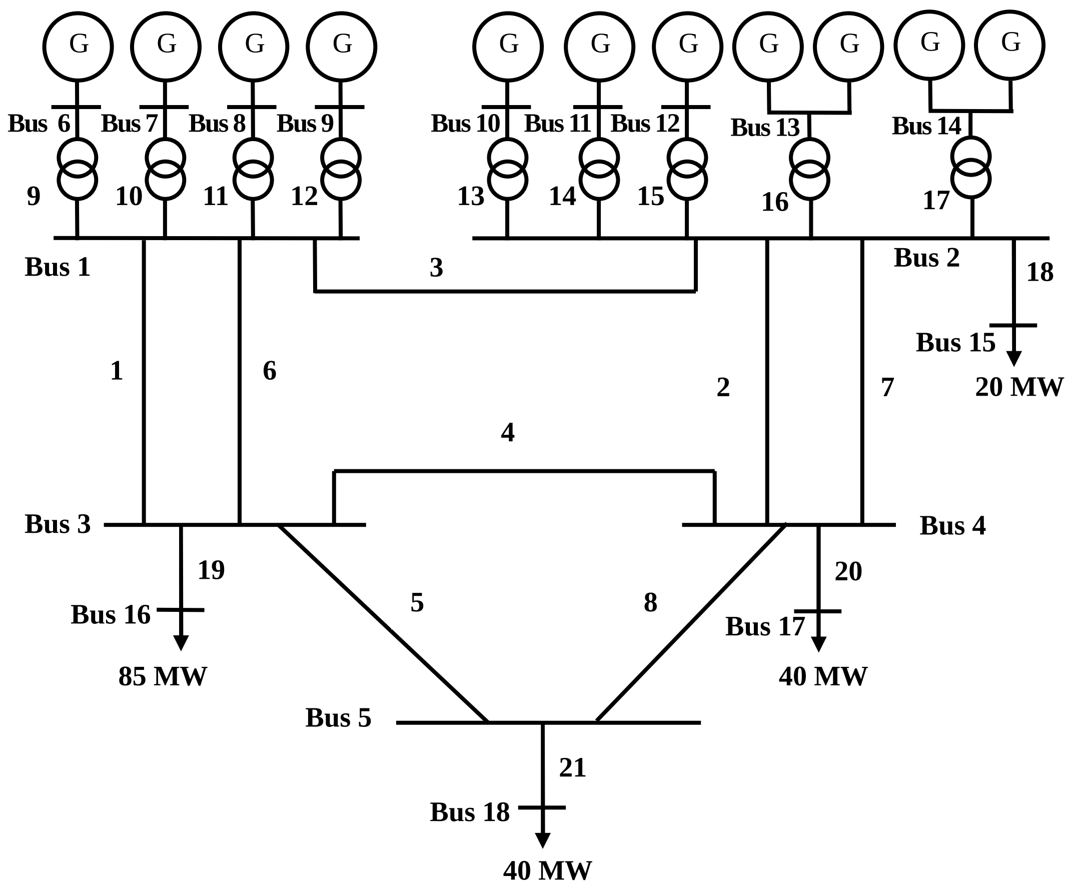

Figure 4.10: Extended single line diagram of the modified RBTS including station related outages

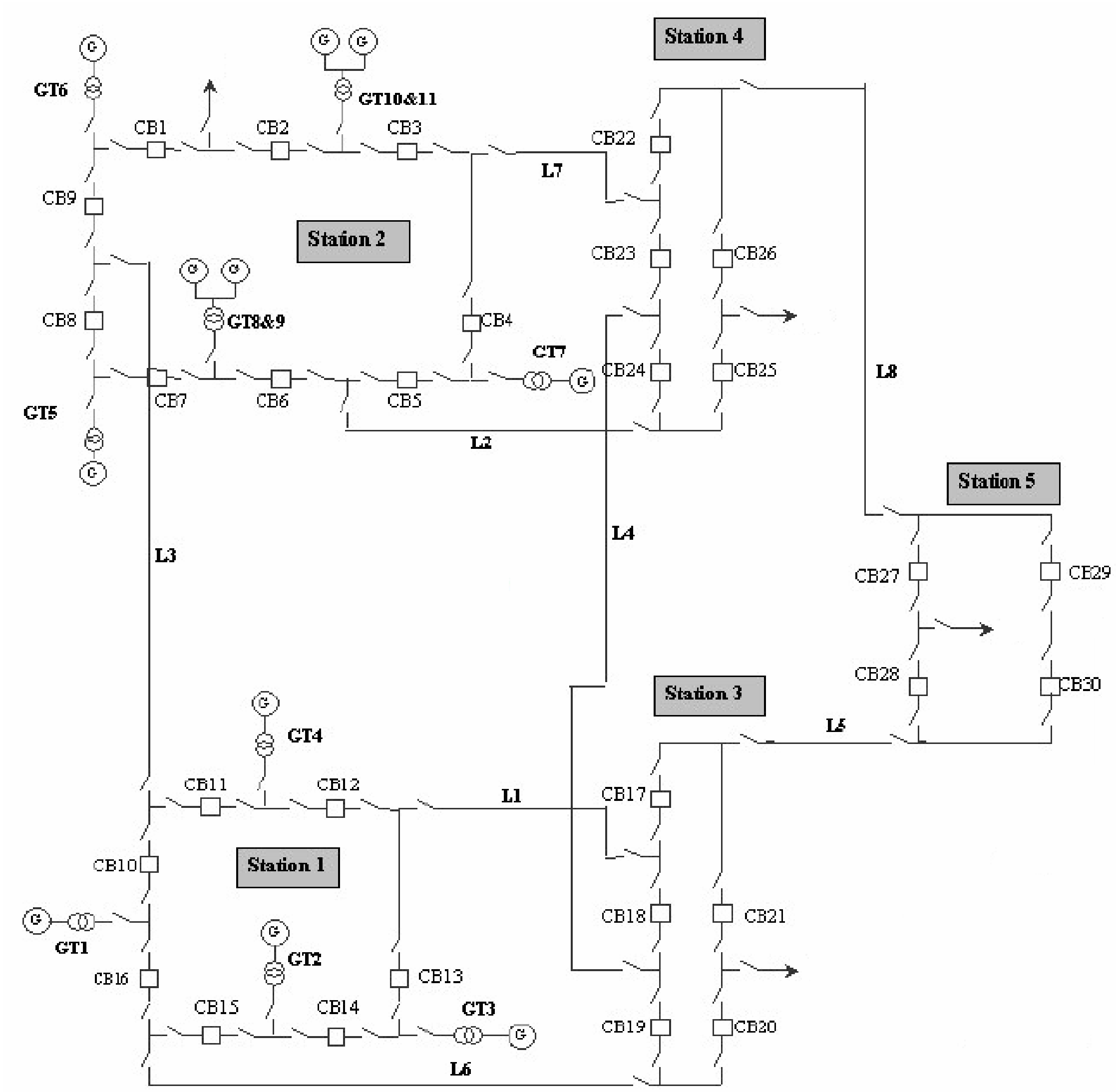

Figure 4.11: Single line diagram of the modified RBTS with ring bus configurations

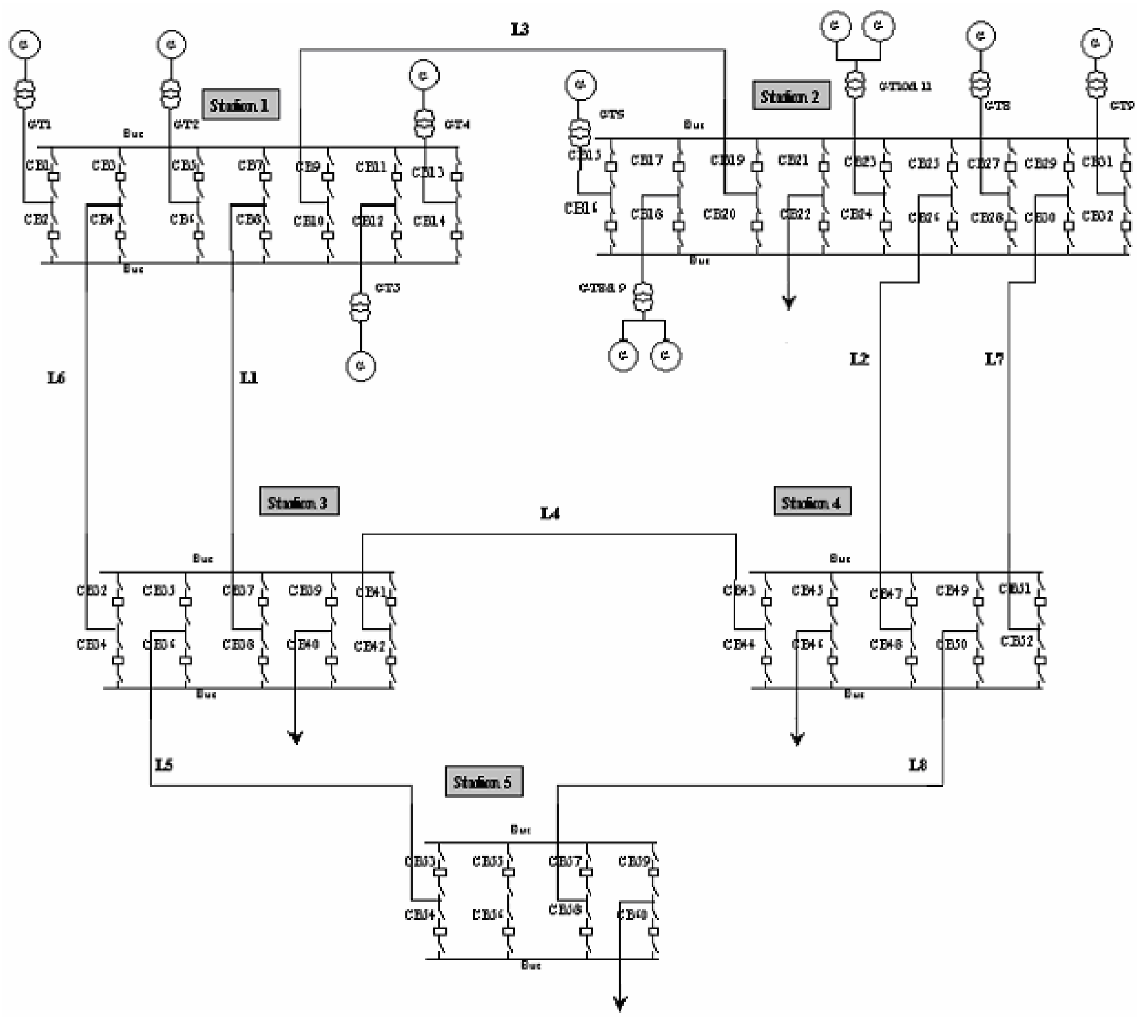

Figure 4.12: Single line diagram of the modified RBTS with double bus double breaker configurations

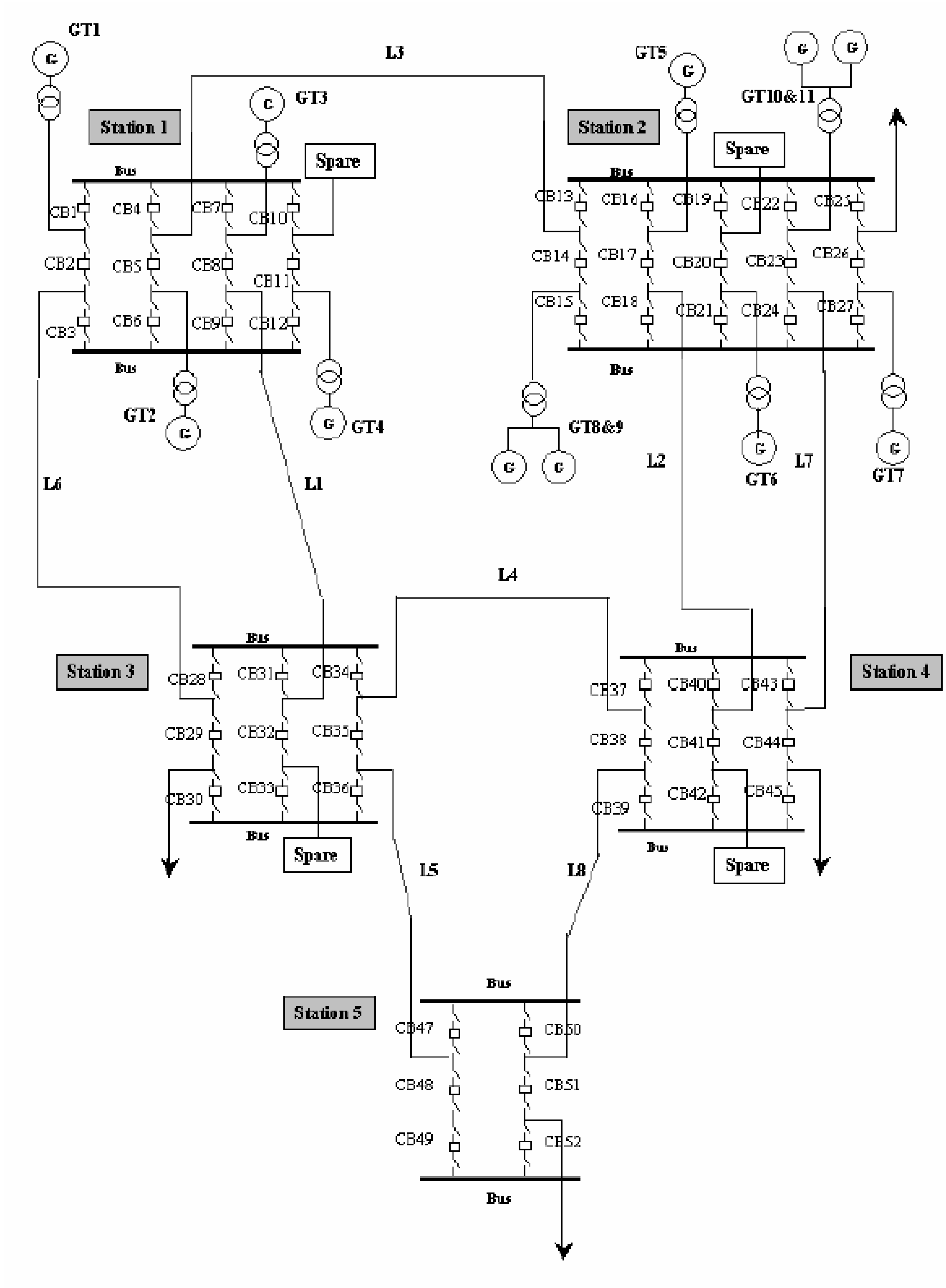

Figure 4.13: Single line diagram of the modified RBTS with one and one half breaker configurations

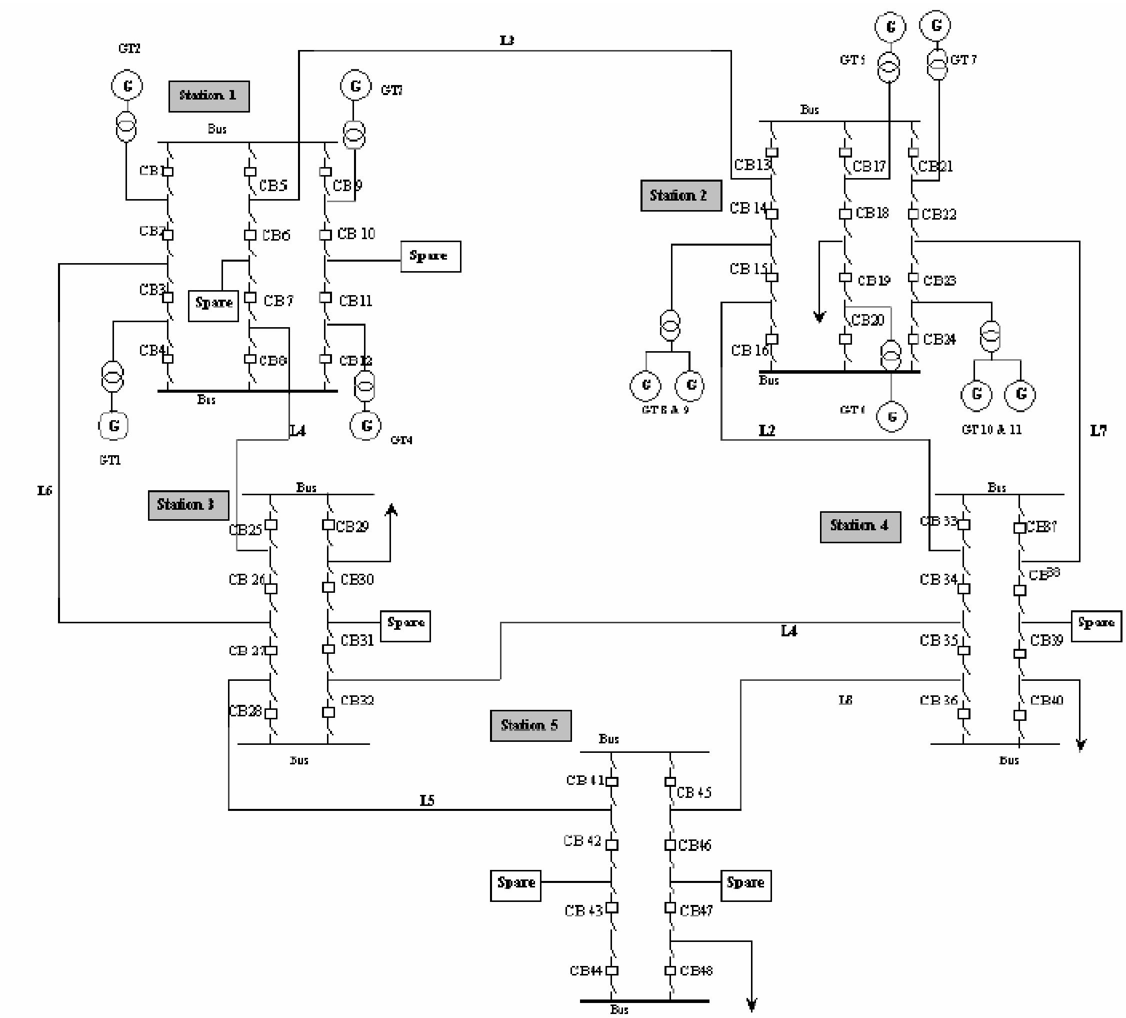

Figure 4.14: Single line diagram of the modified RBTS with one and one third breaker configurations

Reliability indices for the modified RBTS with ring bus configurations

The load point and system reliability indices obtained for the modified RBTS with ring bus schemes, without and with station maintenance outages are shown in Tables 4.11 and 4.12 respectively. Table 4.13 shows the increase in the EENS associated with station related maintenance outages.

Table 4.11: Annual load point indices of the modified RBTS with ring bus schemes

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (Maintenance)
15	0.00004	0.09210	1.178	0.00047	4.09	4.202
16	0.00023	0.28118	8.803	0.00363	31.765	36.621
17	0.00003	0.10856	2.758	0.00077	6.758	6.759
18	0.00004	0.09522	2.340	0.00090	7.915	7.992

Table 4.12: Annual system indices of the modified RBTS with ring bus schemes

Annual Indices	Without mainte.	Maintenance
ENLC (1/yr)	0.57102	0.72091
ADLC (hrs/disturbance)	4.997	4.544
EDLC (hrs/yr)	2.85	3.28
PLC	0.00033	0.00037
EDNS (MW)	0.00577	0.00634
EENS (MWh/yr)	50.52851	55.57458
EDC (k$/yr)	223.34	245.64
BPII (MW/MW-yr)	0.082	0.092
BPECI (MWh/MW-yr)	0.273	0.300
BPACI (MW/disturbance)	26.409	23.589
MBECI (MW/MW)	0.00003	0.00003
SI (system minutes/yr)	16.388	18.024

Table 4.13: Load point and system EENS without and with station maintenance outages for the modified RBTS with ring bus schemes

Load bus No.	EENS (without maintenance)	EENS (including maintenance)	Increase rate (%)
Bus 15	4.09	4.202	2.74
Bus 16	31.765	36.621	15.29
Bus 17	6.758	6.759	0.01
Bus 18	7.915	7.992	0.97
System	50.52851	55.57458	9.99

Reliability indices for the modified RBTS with double bus double breaker configurations

The load point and system reliability indices obtained for the modified RBTS with double bus double breaker schemes, without and with station maintenance outages are shown in Tables 4.14 and 4.15 respectively. Table 4.16 shows the increase in the EENS associated with station related maintenance outages.

Table 4.14: Annual load point indices of the modified RBTS with double bus double breaker schemes

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (Maintenance)
15	0.00000	0.02687	0.344	0.00004	0.336	0.448
16	0.00020	0.14044	2.959	0.00236	20.710	25.827
17	0.00000	0.01428	0.346	0.00004	0.370	0.372
18	0.00001	0.01767	0.362	0.00011	0.964	1.492

Table 4.15: Annual system indices of the modified RBTS with double bus double breaker schemes

Annual Indices	Without mainte.	Maintenance
ENLC (1/yr)	0.19320	0.23090
ADLC (hrs/disturbance)	9.46	9.84
EDLC (hrs/yr)	1.827	2.272
PLC	0.00021	0.00026
EDNS (MW)	0.003	0.003
EENS (MWh/yr)	22.38032	28.13848
EDC (k$/yr)	98.921	124.372
BPII (MW/MW-yr)	0.02168	0.02499
BPECI (MWh/MW-yr)	0.121	0.152
BPACI (MW/disturbance)	20.76	20.03
MBECI (MW/MW)	0.00001	0.00002
SI (system minutes/yr)	7.258	9.126

Table 4.16: Load point and system EENS without and with station maintenance outages for the modified RBTS with double bus double breaker schemes

Load bus No.	EENS (without maintenance)	EENS (including maintenance)	Increase rate (%)
Bus 15	0.336	0.448	33.33
Bus 16	20.710	25.827	24.71
Bus 17	0.370	0.372	0.54
Bus 18	0.964	1.492	54.77
System	22.38032	28.13848	25.73

Reliability indices for the modified RBTS with one and one half breaker configurations

Tables 4.17 and 4.18 show the reliability indices for the modified RBTS with one and one half breaker schemes, without and with station maintenance outages. Table 4.19 shows the increase in the EENS associated with station related maintenance outages.

Table 4.17: Annual load point indices of the modified RBTS with one and one half breaker schemes

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (Maintenance)
15	0.00000	0.01905	0.244	0.00002	0.168	0.168
16	0.00020	0.14813	2.713	0.00231	20.231	26.303
17	0.00000	0.01196	0.286	0.00003	0.258	0.484
18	0.00001	0.03390	0.776	0.00010	0.852	1.156

Table 4.18: Annual system indices of the modified RBTS with one and one half breaker schemes

Annual Indices	Without mainte.	Maintenance
ENLC (1/yr)	0.20703	0.29213
ADLC (hrs/disturbance)	8.68	7.70
EDLC (hrs/yr)	1.796	2.250
PLC	0.00021	0.00026
EDNS (MW)	0.00246	0.00321
EENS (MWh/yr)	21.50983	28.11046
EDC (k$/yr)	95.073	124.248
BPII (MW/MW-yr)	0.02172	0.031
BPECI (MWh/MW-yr)	0.116	0.152
BPACI (MW/disturbance)	19.413	19.626
MBECI (MW/MW)	0.00001	0.00002
SI (system minutes/yr)	6.976	9.117

Table 4.19: Load point and system EENS without and with station maintenance outages for the modified RBTS with one and one half breaker schemes

Load bus No.	EENS (without maintenance)	EENS (including maintenance)	Increase rate (%)
Bus 15	0.168	0.168	0.00
Bus 16	20.231	26.303	30.01
Bus 17	0.258	0.484	87.60
Bus 18	0.852	1.156	35.68
System	21.50983	28.11046	30.69

Reliability indices for the modified RBTS with one and one third breaker configurations

Tables 4.20 and 4.21 show the load point and system reliability indices for the modified RBTS with one and one third breaker schemes, without and with station maintenance outages. Table 4.22 shows the increase in the EENS associated with station related maintenance outages.

Table 4.20: Annual load point indices of the modified RBTS with one and one third breaker schemes

Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (Maintenance)
15	0.00000	0.02426	0.310	0.00001	0.112	0.224
16	0.00020	0.16222	3.405	0.00237	20.731	26.324
17	0.00000	0.01405	0.340	0.00004	0.37	0.708
18	0.00001	0.03792	0.876	0.00011	0.964	1.604

Table 4.21: Annual system indices of the modified RBTS with one and one third breaker schemes

Annual Indices	Without mainte.	Maintenance
ENLC (1/yr)	0.23244	0.32584
ADLC (hrs/disturbance)	7.792	7.004
EDLC (hrs/yr)	1.811	2.282
PLC	0.00021	0.00026
EDNS (MW)	0.00253	0.00329
EENS (MWh/yr)	22.17742	28.86010
EDC (k$/yr)	98.024	127.562
BPII (MW/MW-yr)	0.02665	0.03352
BPECI (MWh/MW-yr)	0.120	0.156
BPACI (MW/disturbance)	21.213	19.029
MBECI (MW/MW)	0.00001	0.00002
SI (system minutes/yr)	7.193	9.360

Table 4.22: Load point and system EENS without and with station maintenance outages for the modified RBTS with one and one third breaker schemes

Load bus No.	EENS (without maintenance)	EENS (including maintenance)	Increase rate (%)
Bus 15	0.112	0.224	100.00
Bus 16	20.731	26.324	26.98
Bus 17	0.370	0.708	91.35
Bus 18	0.964	1.604	66.39
System	22.17742	28.86010	30.13

Comparison of the modified RBTS with the four different station configurations

The base case reliability indices for the modified RBTS without incorporating station related outages are shown in Tables 4.9 and 4.10. Comparisons of the increase in the annual system indices without and with station maintenance outages for the modified RBTS with four different station schemes are shown in Figures 4.15 and 4.16 respectively.

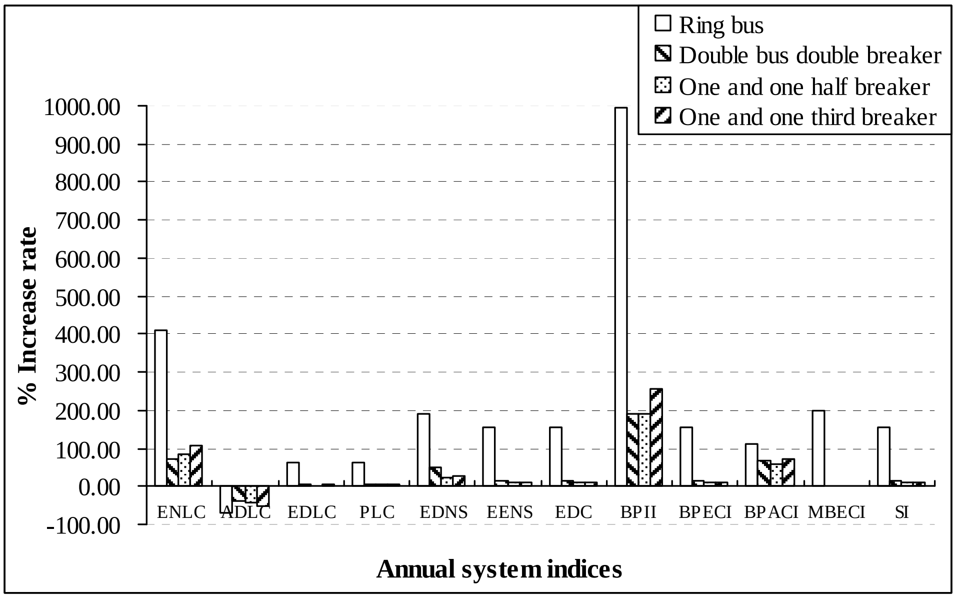

Figure 4.15: System reliability comparison for the modified RBTS with the four different station configurations (without considering station maintenance outages)

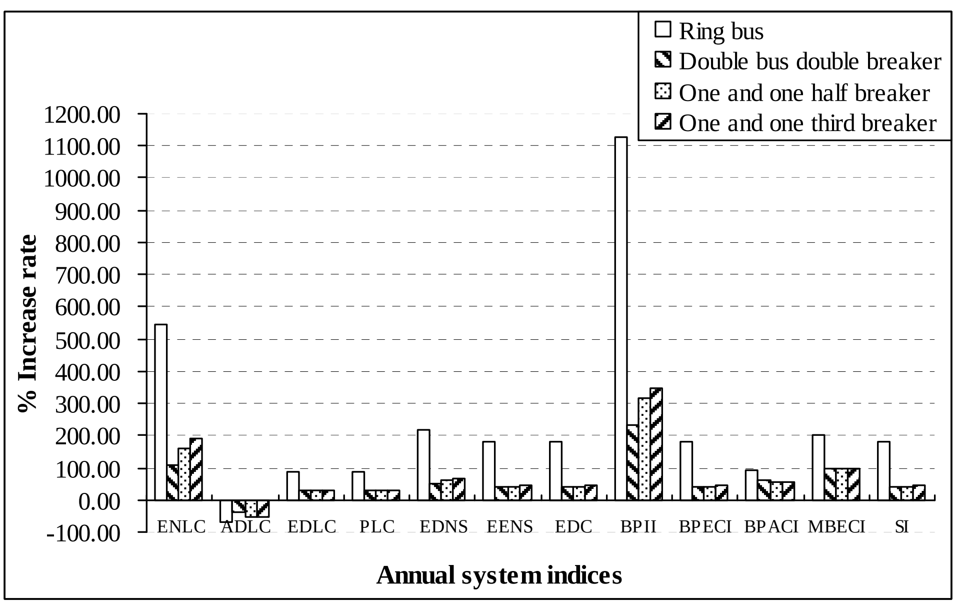

Figure 4.16: System reliability comparison for the modified RBTS with the four different station configurations (considering station maintenance outages)

It can be seen from Tables 4.13, 4.16, 4.19 and 4.22 that the load point and system EENS increase at different rates for the four different station schemes after including maintenance outages. The results also show the major contribution to the increase in the system EENS is from the Bus 16 which carries the heaviest load in the system.

The system reliability indices of the modified RBTS with four different station schemes degrade when station maintenance outages are incorporated. The modified RBTS with ring bus schemes is the least reliable system whether station maintenance outages are included or not. The system indices of EENS, SI, etc. are very similar for the modified RBTS with double bus double breaker, one and one half breaker and one and one third breaker configurations. This may not be the case when the station component reliability data changes.

It is important and necessary to perform sensitivity analyses because variations in the reliability data of station components can have large impacts on the composite system reliability. Sensitivity studies are conducted using the modified RBTS with the four different station schemes in the next chapter.

4.4 IEEE-RTS Analysis

The RBTS is a small composite system and easily used to incorporate station related outages. The IEEE-RTS is a comparatively large and complex system and contains 24 buses. The single line diagram of the IEEE-RTS is shown in Figure 2.2. The proposed techniques to incorporate station related outages have been applied in an IEEE-RTS reliability evaluation. The reliability data for the individual station equipment are given in Section 3.3. The extended single line diagram of the IEEE-RTS incorporating station related outages is shown in Figure 4.17 [28]. The data for the connected terminal components in this figure are modified to include the station related outages.

The analysis in this case was conducted in several steps. First is a reliability evaluation for the IEEE-RTS with ring bus configurations. Several ring bus stations were then changed to one and one half breaker stations in order to improve the IEEE-RTS reliability. Reliability analysis for the IEEE-RTS with mixed ring bus and one and one half breaker station configurations was then conducted.

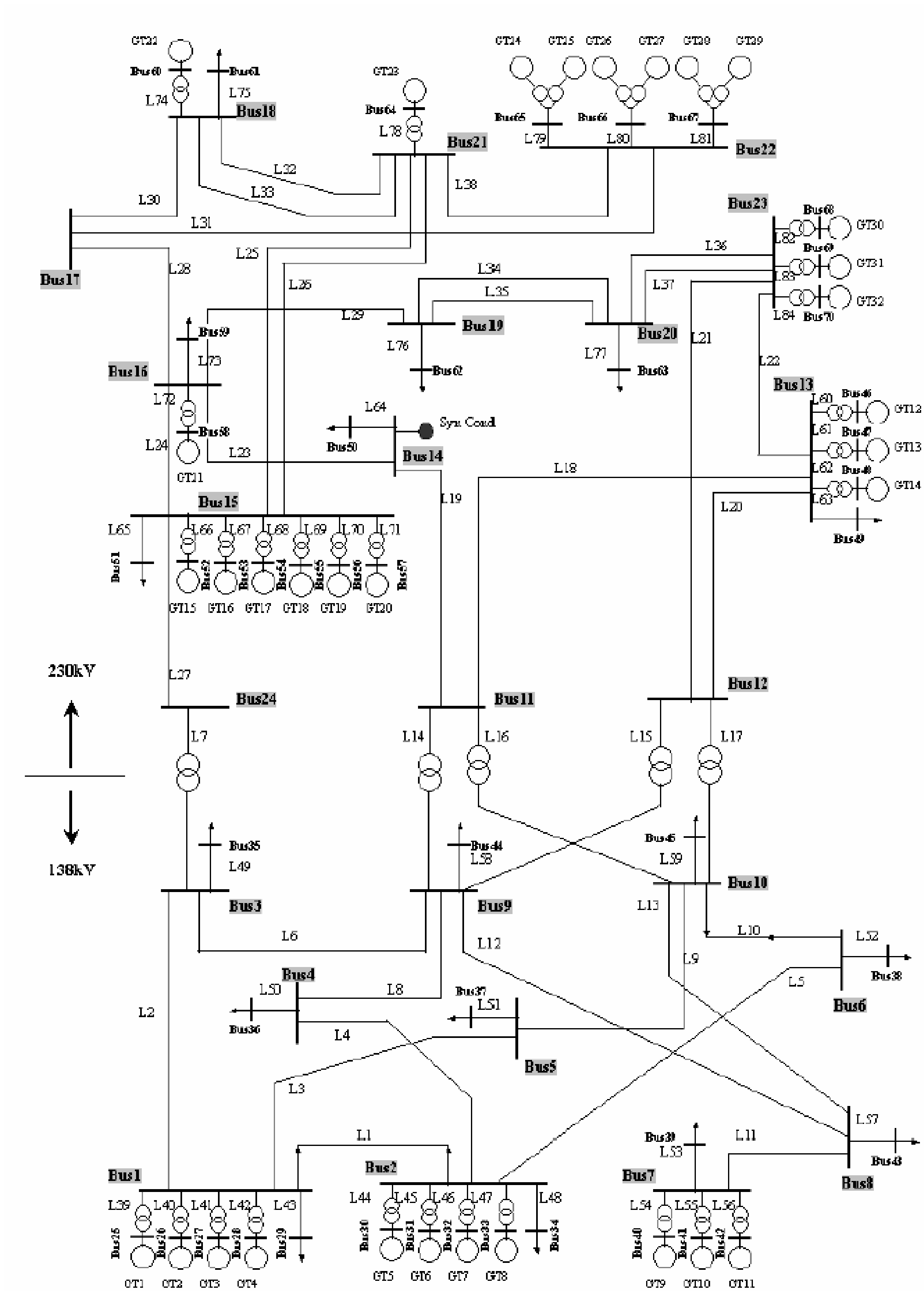

Figure 4.17: Extended single line diagram of the IEEE-RTS including station related outages

4.4.1 Base Case Analysis for the IEEE-RTS with Ring Bus Configurations

The single line diagram of the IEEE-RTS with ring bus configurations is shown in Figure 4.18 [28]. The modified generator reliability data of the IEEE-RTS with ring bus schemes are shown in Table A.11. The modified data for the transmission lines, transformers and equivalent load circuits without and with station related maintenance outages for the IEEE-RTS with ring bus schemes are presented in Tables D.1 and D.2 respectively.

The annual reliability indices, without and with station maintenance outages, were evaluated for the IEEE-RTS with ring bus schemes and are shown in Tables 4.23 to 4.26.

Without considering station maintenance outages

Table 4.23: Annual load point indices with and without station related forced outages for the IEEE-RTS with ring bus schemes

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (without station)	Increase (MWh/yr)
1	29	0.00006	0.15166	10.477	0.00401	35.098	-	35.10
2	34	0.00006	0.12508	7.729	0.00376	32.902	0.386	32.52
3	35	0.00007	0.16428	18.843	0.00762	66.718	0.223	66.50
4	36	0.00008	0.34366	16.266	0.00388	34	-	34.00
5	37	0.00009	0.39154	17.779	0.00418	36.601	-	36.60
6	38	0.00010	0.36101	31.405	0.00870	76.204	0.293	75.91
7	39	0.00009	0.20064	16.042	0.00736	64.437	0.020	64.42
8	43	0.00008	0.27622	30.200	0.00831	72.822	0.004	72.82
9	44	0.00119	1.20769	86.127	0.07732	677.362	602.035	75.33
10	45	0.00009	0.23290	28.717	0.01121	98.168	2.388	95.78
13	49	0.00008	0.22762	38.570	0.01322	115.839	0.041	115.80
14	50	0.00026	0.41331	38.877	0.01874	164.168	108.304	55.86
15	51	0.00072	0.76579	87.052	0.06721	588.76	484.203	104.56
16	59	0.00015	0.33863	19.308	0.00705	61.758	30.930	30.83
18	61	0.00009	0.35000	70.212	0.01505	131.837	21.298	110.54
19	62	0.00206	2.09807	153.856	0.13497	1182.313	1111.382	70.93
20	63	0.00011	0.30815	22.985	0.00710	62.225	22.733	39.49

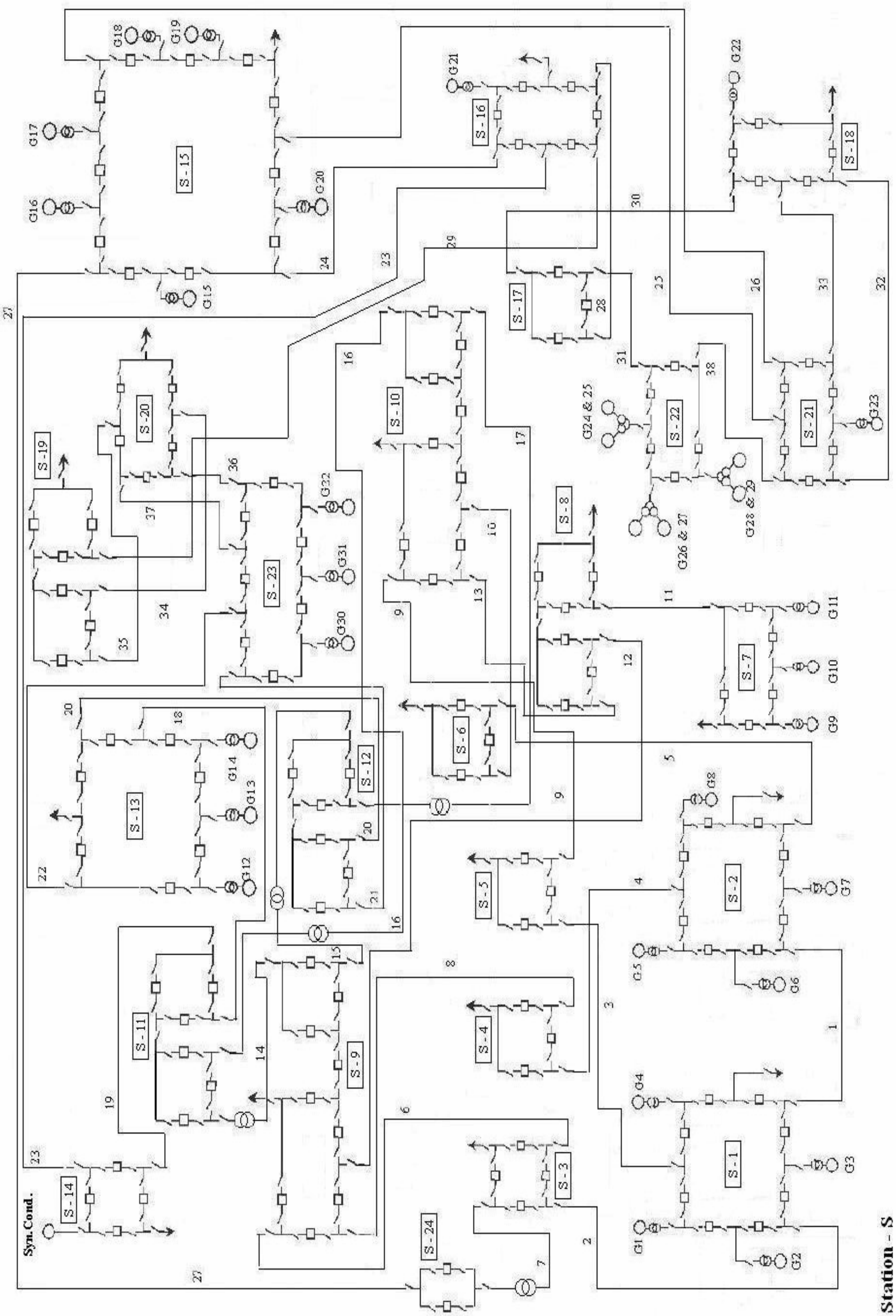

Figure 4.18: Single line diagram of the IEEE-RTS with ring bus configurations

Table 4.24: Annual system indices with and without station related outages for the IEEE-RTS with ring bus schemes

Indices	Annual	Annual (without station)
ENLC (1/yr)	5.99825	1.63246
ADLC (hrs/disturbance)	4.68514	10.67693
EDLC (hrs/yr)	28.10	17.43
PLC	0.00321	0.00199
EDNS (MW)	0.39968	0.27217
EENS (MWh/yr)	3501.206	2384.23
EDC (k$/yr)	14775.090	10061.47
BPII (MW/MW-yr)	0.244	0.081
BPECI (MWh/MW-yr)	1.228	0.837
BPACI (MW/disturbance)	115.77	140.68
MBECI (MW/MW)	0.00014	0.00010
SI (system minutes/yr)	73.71	50.19

It can be seen from Table 4.23 that the EENS index for the load points at generating stations 13, 15 and 18 increases significantly after incorporating station related outages into the IEEE-RTS. These stations could be modified to one and one half or double bus double breaker configurations in order to improve their reliability performances. The EENS index for the load points at Stations 3, 6, 8, 9, 10 and 19 also increase significantly by incorporating station related outages in the IEEE-RTS reliability evaluation. These stations are possible candidates for modification to improve the IEEE-RTS reliability.

Considering station maintenance outages

Table 4.25: Annual load point indices with and without station maintenance outages for the IEEE-RTS with ring bus schemes

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (Table 4.23)	Increase rate (%)
1	29	0.00006	0.16326	11.278	0.00442	38.729	35.098	10.35
2	34	0.00007	0.12032	7.424	0.00414	36.225	32.902	10.10
3	35	0.00007	0.16769	19.221	0.00808	70.816	66.718	6.14
4	36	0.00008	0.34596	16.375	0.00398	34.829	34	2.44
5	37	0.00009	0.39140	17.772	0.00418	36.601	36.601	0.00
6	38	0.00010	0.36264	31.546	0.00887	77.728	76.204	2.00
7	39	0.00010	0.21562	17.240	0.00800	70.040	64.437	8.70
8	43	0.00008	0.27926	30.532	0.00875	76.655	72.822	5.26
9	44	0.00127	1.28643	90.866	0.08206	718.873	677.362	6.13

Table 4.25: (Continued)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (Table 4.23)	Increase rate (%)
10	45	0.00010	0.25003	30.801	0.01250	109.460	98.168	11.50
13	49	0.00008	0.23447	39.726	0.01424	124.765	115.839	7.71
14	50	0.00028	0.42789	39.621	0.02005	175.650	164.168	6.99
15	51	0.00077	0.83825	96.062	0.07300	639.453	588.76	8.61
16	59	0.00016	0.35484	20.087	0.00774	67.833	61.758	9.84
18	61	0.00010	0.40890	82.168	0.01660	145.437	131.837	10.32
19	62	0.00220	2.24327	163.532	0.14418	1263.000	1182.313	6.82
20	63	0.00012	0.31648	23.452	0.00753	65.952	62.225	5.99

Table 4.26: Annual system indices with and without station maintenance outages for the IEEE-RTS with ring bus schemes

Indices	Annual	Annual (Table 4.24)
ENLC (1/yr)	6.27805	5.99825
ADLC (hrs/disturbance)	4.76981	4.68514
EDLC (hrs/yr)	29.95	28.10
PLC	0.00342	0.00321
EDNS (MW)	0.42832	0.39968
EENS (MWh/yr)	3752.043	3501.206
EDC (k$/yr)	15833.62	14775.090
BPII (MW/MW-yr)	0.259	0.244
BPECI (MWh/MW-yr)	1.317	1.228
BPACI (MW/disturbance)	117.51	115.77
MBECI (MW/MW)	0.00015	0.00014
SI (system minutes/yr)	78.99	73.71

Tables 4.25 and 4.26 show that the load point and system EENS increase at different rates by incorporating the effects of station maintenance outages. The error in the overall system EENS due to not considering station maintenance outages is approximately 6.6%. The results show that not considering station related maintenance outages underestimates the effects of station related outages on composite system reliability performance. This could lead to improper decisions in the power system planning, design and operation process.

4.4.2 Station Modifications

The IEEE-RTS has a weak generation system and a relatively strong transmission system and therefore the major contribution to the overall system reliability indices are from the generation facilities. The following analysis of station selection assumes that all the generating units are 100% reliable in order to clearly see the effect due to different configurations.

Analysis of the IEEE-RTS with ring bus schemes (generators are 100% reliable)

Tables 4.27 and 4.28 show the annual reliability indices for the IEEE-RTS with and without ring bus schemes. Tables 4.29 and 4.30 show the annual reliability indices with and without station related maintenance outages for the IEEE-RTS with ring bus schemes.

It can be seen from Table 4.27 that the EENS index for the load points at generating station 13, 15 and 18 increases significantly by incorporating station related outages. These stations are modified to one and one half breaker configurations to improve their reliability performances. The EENS index for the load points at Stations 3, 6, 8, 9, 10 and 19 show comparatively large increases by including the effects of station related outages. Selected stations were modified in the following analyses.

Table 4.27: Annual load point indices without considering station maintenance outages for the IEEE-RTS with and without ring bus schemes (Gen. 100% rel.)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (without station)	Increase (MWh/yr)
1	29	0.00006	0.03125	2.159	0.00401	35.098	-	35.10
2	34	0.00006	0.05847	3.628	0.00372	32.611	-	32.61
3	35	0.00007	0.05624	6.468	0.00760	66.567	-	66.57
4	36	0.00008	0.30611	14.489	0.00388	34.000	-	34.00
5	37	0.00009	0.34506	15.668	0.00418	36.601	-	36.60
6	38	0.00010	0.31266	27.198	0.00870	76.204	0.737	75.47
7	39	0.00009	0.11332	9.060	0.00736	64.437	-	64.44
8	43	0.00008	0.06201	6.774	0.00831	72.819	-	72.82
9	44	0.00007	0.12830	14.360	0.00829	72.615	0.049	72.57
10	45	0.00009	0.14866	18.543	0.01098	96.151	-	96.15
13	49	0.00008	0.07036	11.926	0.01322	115.818	-	115.82
14	50	0.00005	0.15636	19.403	0.00645	56.525	0.001	56.52
15	51	0.00006	0.06237	12.646	0.01176	103.033	0.021	103.01
16	59	0.00006	0.08058	5.154	0.00358	31.378	-	31.38
18	61	0.00006	0.07127	15.179	0.01278	111.952	-	111.95
19	62	0.00006	0.13814	15.983	0.00744	65.138	0.231	64.91
20	63	0.00006	0.05818	4.764	0.00458	40.164	-	40.16

Table 4.28: Annual system indices without considering station maintenance outages for the IEEE-RTS with and without ring bus schemes (Gen. 100% rel.)

Indices	Annual	Annual (without station)
ENLC (1/yr)	2.19739	0.00150
ADLC (hrs/disturbance)	4.83	9.55
EDLC (hrs/yr)	10.604	0.014
PLC	0.00121	0.000
EDNS (MW)	0.12684	0.00012
EENS (MWh/yr)	1111.11	1.04
EDC (k$/yr)	4688.89	4.39
BPII (MW/MW-yr)	0.07137	0.00004
BPECI (MWh/MW-yr)	0.38986	0.00036
BPACI (MW/disturbance)	92.56	71.81
MBECI (MW/MW)	0.00004	0.000
SI (system minutes/yr)	23.39	0.02

Table 4.29: Annual load point indices with and without station maintenance outages for the IEEE-RTS with ring bus schemes (Gen. 100% rel.)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (Table 4.27)	Increase rate (%)
1	29	0.00006	0.05088	3.513	0.00442	38.729	35.098	10.35
2	34	0.00007	0.06002	3.732	0.00409	35.872	32.611	10.00
3	35	0.00007	0.05832	6.707	0.00806	70.602	66.567	6.06
4	36	0.00008	0.30707	14.534	0.00398	34.829	34.000	2.44
5	37	0.00009	0.34495	15.663	0.00418	36.601	36.601	0.00
6	38	0.00010	0.31377	27.295	0.00887	77.728	76.204	2.00
7	39	0.00010	0.12686	10.143	0.00800	70.040	64.437	8.70
8	43	0.00008	0.07873	8.603	0.00875	76.652	72.819	5.26
9	44	0.00007	0.12550	14.026	0.00830	72.695	72.615	0.11
10	45	0.00010	0.16010	19.969	0.01222	107.077	96.151	11.36
13	49	0.00008	0.07402	12.547	0.01424	124.727	115.818	7.69
14	50	0.00005	0.16182	20.080	0.00670	58.699	56.525	3.85
15	51	0.00007	0.10907	22.104	0.01339	117.265	103.033	13.81
16	59	0.00006	0.08396	5.370	0.00397	34.740	31.378	10.71
18	61	0.00006	0.12047	25.659	0.01363	119.415	111.952	6.67
19	62	0.00007	0.17264	19.957	0.00863	75.613	65.138	16.08
20	63	0.00006	0.05925	4.851	0.00475	41.598	40.164	3.57

Table 4.30: Annual system indices with and without station maintenance outages for the IEEE-RTS with ring bus schemes (Gen. 100% rel.)

Indices	Annual	Annual (Table 4.28)
ENLC (1/yr)	2.40519	2.19791
ADLC (hrs/disturbance)	4.70	4.82
EDLC (hrs/yr)	11.310	10.604
PLC	0.00129	0.00121
EDNS (MW)	0.13617	0.12684
EENS (MWh/yr)	1192.88	1111.11
EDC (k$/yr)	5033.96	4688.89
BPII (MW/MW-yr)	0.08237	0.07138
BPECI (MWh/MW-yr)	0.419	0.38986
BPACI (MW/disturbance)	97.601	92.56
MBECI (MW/MW)	0.00005	0.00004
SI (system minutes/yr)	25.11	23.39

It can be seen from Tables 4.29 and 4.30 that the load point and system EENS increase with different rates after incorporating station maintenance outages. The major contribution to the increase in the system EENS after incorporating station maintenance outages is from the load point EENS at Station 15. This is the largest station in the IEEE-RTS and contains the most equipment.

It can clearly be seen by comparing Tables 4.23 to 4.26 with Tables 4.27 to 4.30 that generator forced outages create the major contribution to the load point and system indices of the IEEE-RTS.

Selected generating station modifications

Generating stations 13, 15 and 18 were selected to be modified to one and one half breaker configurations. Generation is considered to be 100% reliable in the following studies.

(a) Modification I

Figure 4.19 [28] shows the IEEE-RTS with modified generating stations 13, 15 and 18. Tables 4.31 and 4.32 show the annual reliability indices for the IEEE-RTS with and before generating station modification I. Tables 4.33 and 4.34 show the annual reliability indices without and with station maintenance outages for the IEEE-RTS with generating station modification I.

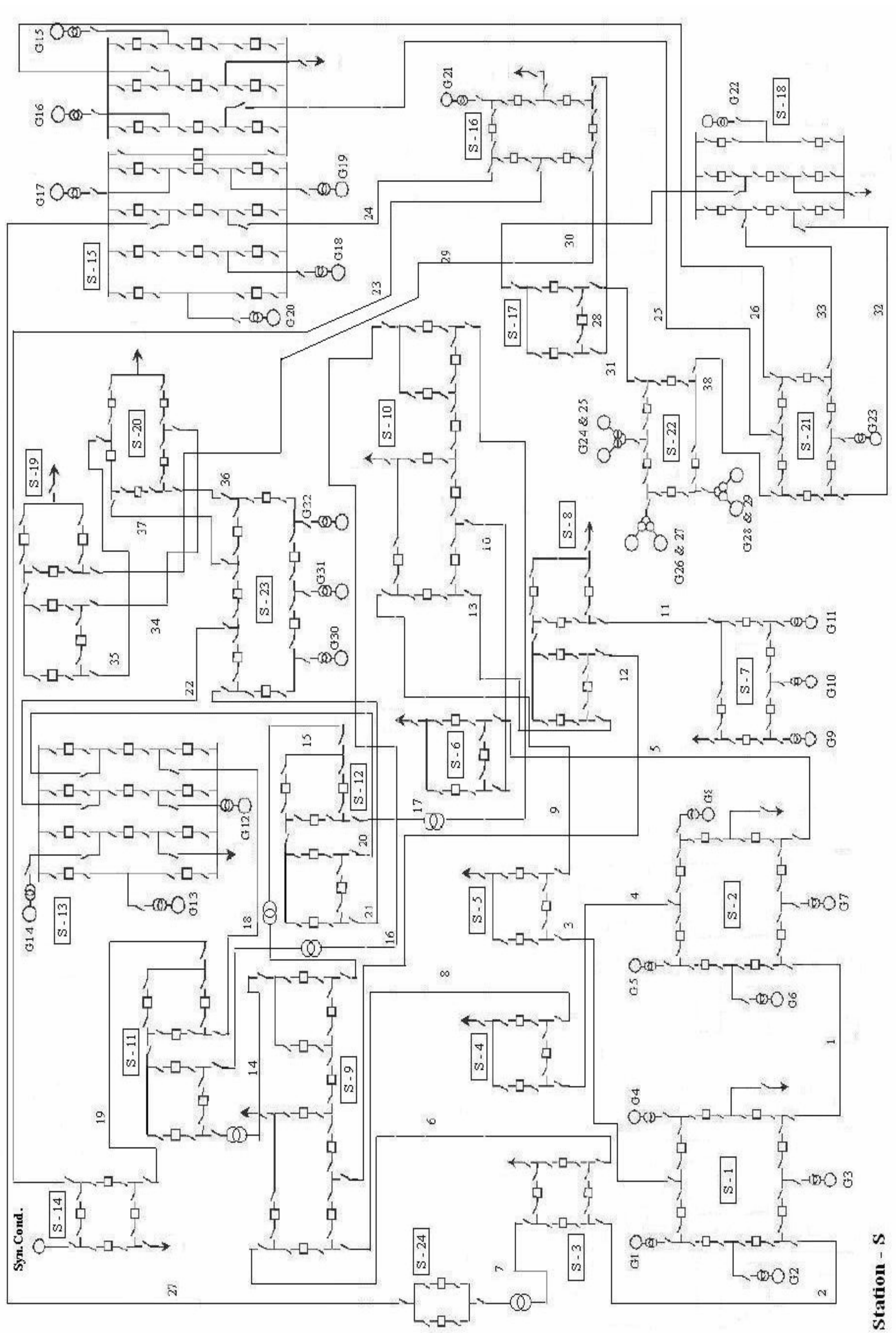

Figure 4.19: IEEE-RTS with modified generating stations 13, 15 and 18

Table 4.31: Annual load point indices without considering station maintenance outages for the IEEE-RTS with and without generating station modification I (Gen. 100% rel.)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (before modification)	Decrease rate (%)
1	29	0.00006	0.04465	3.084	0.00414	36.309	35.098	-3.45
2	34	0.00006	0.02698	1.674	0.00347	30.437	32.611	6.67
3	35	0.00007	0.03995	4.592	0.00760	66.567	66.567	0.00
4	36	0.00008	0.30633	14.499	0.00388	34.000	34.000	0.00
5	37	0.00009	0.34531	15.680	0.00418	36.601	36.601	0.00
6	38	0.00010	0.31300	27.228	0.00870	76.204	76.204	0.00
7	39	0.00010	0.11582	9.260	0.00768	67.238	64.437	-4.35
8	43	0.00008	0.06246	6.824	0.00831	72.819	72.819	0.00
9	44	0.00007	0.12940	14.484	0.00829	72.615	72.615	0.00
10	45	0.00009	0.14898	18.582	0.01098	96.151	96.151	0.00
13	49	0.00004	0.22935	38.876	0.00678	59.394	115.818	48.72
14	50	0.00006	0.18162	22.538	0.00695	60.873	56.525	-7.69
15	51	0.00002	0.17797	36.084	0.00487	42.641	103.033	58.61
16	59	0.00006	0.09315	5.958	0.00397	34.740	31.378	-10.71
18	61	0.00003	0.22157	47.193	0.00639	55.976	111.952	50.00
19	62	0.00006	0.08561	9.904	0.00697	61.080	65.138	6.23
20	63	0.00007	0.14656	11.999	0.00540	47.336	40.164	-17.86

Table 4.32: Annual system indices without considering station maintenance outages for the IEEE-RTS with and without generating station modification I (Gen. 100% rel.)

Indices	Annual	Annual (before modification)
ENLC (1/yr)	2.66678	2.19791
ADLC (hrs/disturbance)	3.70	4.82
EDLC (hrs/yr)	9.868	10.604
PLC	0.00113	0.00121
EDNS (MW)	0.10856	0.12684
EENS (MWh/yr)	950.98	1111.11
EDC (k$/yr)	4013.14	4688.89
BPII (MW/MW-yr)	0.10121	0.07138
BPECI (MWh/MW-yr)	0.33368	0.38986
BPACI (MW/disturbance)	108.17	92.56
MBECI (MW/MW)	0.00004	0.00004
SI (system minutes/yr)	20.02	23.39

It can be seen from Table 4.31 that the load point EENS at Stations 13, 15 and 18 and the system EENS decreases greatly after modifying generating stations 13, 15 and 18 to one and one half breaker configurations. The EENS index at some other load points decreases while that at some other points increases.

Table 4.33: Annual load point indices with and without station maintenance outages for the IEEE-RTS with generating station modification I (Gen. 100% rel.)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (Table 4.31)	Increase rate (%)
1	29	0.00006	0.06888	4.758	0.00428	37.519	36.309	3.33
2	34	0.00006	0.03246	2.014	0.00397	34.785	30.437	14.29
3	35	0.00007	0.04206	4.834	0.00806	70.602	66.567	6.06
4	36	0.00008	0.30740	14.550	0.00398	34.829	34.000	2.44
5	37	0.00009	0.34520	15.674	0.00418	36.601	36.601	0.00
6	38	0.00010	0.31420	27.332	0.00887	77.728	76.204	2.00
7	39	0.00010	0.12961	10.363	0.00832	72.842	67.238	8.33
8	43	0.00008	0.07910	8.643	0.00875	76.652	72.819	5.26
9	44	0.00007	0.12664	14.160	0.00830	72.707	72.615	0.13
10	45	0.00010	0.16041	20.008	0.01222	107.077	96.151	11.36
13	49	0.00006	0.23160	39.257	0.00949	83.151	59.394	40.00
14	50	0.00006	0.17574	21.808	0.00720	63.047	60.873	3.57
15	51	0.00003	0.15690	31.803	0.00528	46.218	42.641	8.39
16	59	0.00007	0.11255	7.199	0.00435	38.102	34.740	9.68
18	61	0.00003	0.20378	43.404	0.00724	63.439	55.976	13.33
19	62	0.00007	0.10609	12.184	0.00817	71.575	61.080	17.18
20	63	0.00007	0.16301	13.346	0.00557	48.770	47.336	3.03

Table 4.34: Annual system indices with and without station maintenance outages for the IEEE-RTS with generating station modification I (Gen. 100% rel.)

Indices	Annual	Annual (Table 4.32)
ENLC (1/yr)	2.75331	2.66728
ADLC (hrs/disturbance)	3.845	3.70
EDLC (hrs/yr)	10.592	9.868
PLC	0.00121	0.00113
EDNS (MW)	0.11822	0.10856
EENS (MWh/yr)	1035.65	950.98
EDC (k$/yr)	4370.42	4013.14
BPII (MW/MW-yr)	0.10226	0.10123
BPECI (MWh/MW-yr)	0.363	0.33368
BPACI (MW/disturbance)	105.81	108.16
MBECI (MW/MW)	0.00004	0.00004
SI (system minutes/yr)	21.80	20.02

It can be seen from Table 4.33 that the load point EENS at Station 13 increases significantly after including station maintenance outages due to the design of Station 13 in the first modification.

(b) Modification II

Stations 15 and 18 are identical to those shown in Figure 4.19. Figure D.1 (Appendix D) shows the modifications made at Station 13. Line 18 and the load point are interchanged in this modification. The annual reliability indices for the IEEE-RTS with and without generating station modification II are shown in Tables 4.35 and 4.36. The annual reliability indices without and with station maintenance outages for the IEEE-RTS with generating station modification II are shown in Tables 4.37 and 4.38.

Table 4.35: Annual load point indices without considering maintenance outages for the IEEE-RTS with and without generating station modification II (Gen. 100% rel.)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (before modification)	Decrease rate (%)
1	29	0.00007	0.03564	2.462	0.00456	39.940	35.098	-13.80
2	34	0.00007	0.03227	2.002	0.00409	35.872	32.611	-10.00
3	35	0.00007	0.03995	4.592	0.00760	66.567	66.567	0.00
4	36	0.00008	0.30633	14.499	0.00388	34.000	34.000	0.00
5	37	0.00009	0.34531	15.680	0.00418	36.601	36.601	0.00
6	38	0.00010	0.31300	27.228	0.00870	76.204	76.204	0.00
7	39	0.00009	0.12664	10.125	0.00720	63.036	64.437	2.17
8	43	0.00008	0.06246	6.824	0.00831	72.819	72.819	0.00
9	44	0.00007	0.12940	14.483	0.00829	72.615	72.615	0.00
10	45	0.00009	0.14898	18.582	0.01098	96.151	96.151	0.00
13	49	0.00004	0.28368	48.084	0.00644	56.424	115.818	51.28
14	50	0.00006	0.18163	22.538	0.00695	60.873	56.525	-7.69
15	51	0.00003	0.21336	43.260	0.00568	49.746	103.033	51.72
16	59	0.00005	0.07572	4.843	0.00320	28.016	31.378	10.71
18	61	0.00003	0.26014	55.410	0.00724	63.439	111.952	43.33
19	62	0.00006	0.09760	11.292	0.00674	59.052	65.138	9.34
20	63	0.00005	0.06034	4.940	0.00377	32.992	40.164	17.86

Table 4.36: Annual system indices without considering maintenance outages for the IEEE-RTS with and without generating station modification II (Gen. 100% rel.)

Indices	Annual	Annual (before modification)
ENLC (1/yr)	2.71051	2.19791
ADLC (hrs/disturbance)	3.58	4.82
EDLC (hrs/yr)	9.710	10.604
PLC	0.00111	0.00121
EDNS (MW)	0.10780	0.12684
EENS (MWh/yr)	944.35	1111.11
EDC (k$/yr)	3985.14	4688.89
BPII (MW/MW-yr)	0.10767	0.07138

Table 4.36: (Continued)

Indices	Annual	Annual (before modification)
BPECI (MWh/MW-yr)	0.33135	0.38986
BPACI (MW/disturbance)	113.21	92.56
MBECI (MW/MW)	0.00004	0.00004
SI (system minutes/yr)	19.88	23.39

Table 4.37: Annual load point indices with and without station maintenance outages for the IEEE-RTS with generating station modification II (Gen. 100% rel.)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (Table 4.35)	Increase rate (%)
1	29	0.00007	0.05447	3.763	0.00484	42.360	39.940	6.06
2	34	0.00007	0.04755	2.950	0.00459	40.220	35.872	12.12
3	35	0.00007	0.04206	4.834	0.00806	70.602	66.567	6.06
4	36	0.00008	0.30740	14.550	0.00398	34.829	34.000	2.44
5	37	0.00009	0.34520	15.674	0.00418	36.601	36.601	0.00
6	38	0.00010	0.31419	27.322	0.00887	77.728	76.204	2.00
7	39	0.00010	0.12960	10.362	0.00800	70.040	63.036	11.11
8	43	0.00008	0.07917	8.651	0.00875	76.652	72.819	5.26
9	44	0.00007	0.12639	14.141	0.00830	72.689	72.615	0.10
10	45	0.00010	0.16041	20.008	0.01222	107.077	96.151	11.36
13	49	0.00004	0.23976	40.640	0.00644	56.424	56.424	0.00
14	50	0.00006	0.17574	21.808	0.00720	63.047	60.873	3.57
15	51	0.00003	0.19237	38.999	0.00609	53.319	49.746	7.18
16	59	0.00006	0.09543	6.104	0.00358	31.378	28.016	12.00
18	61	0.00004	0.24521	52.229	0.00809	70.903	63.439	11.77
19	62	0.00007	0.11728	13.547	0.00794	69.513	59.052	17.71
20	63	0.00005	0.07651	6.264	0.00393	34.426	32.992	4.35

Table 4.38: Annual system indices with and without station maintenance outages for the IEEE-RTS with generating station modification II (Gen. 100% rel.)

Indices	Annual	Annual (Table 4.36)
ENLC (1/yr)	2.74671	2.71051
ADLC (hrs/disturbance)	3.760	3.58
EDLC (hrs/yr)	10.328	9.710
PLC	0.00118	0.00111
EDNS (MW)	0.11505	0.10780
EENS (MWh/yr)	1007.81	944.35
EDC (k$/yr)	4252.95	3985.14
BPII (MW/MW-yr)	0.10591	0.10767
BPECI (MWh/MW-yr)	0.354	0.33135
BPACI (MW/disturbance)	109.90	113.21
MBECI (MW/MW)	0.00004	0.00004
SI (system minutes/yr)	21.22	19.88

Comparing Tables 4.35 and 4.31, most of the load point EENS on the 230kV side of the IEEE-RTS decrease with different rates in modification II. The overall system EENS is also smaller for modification II than that for modification I.

Comparing Tables 4.37 and 4.33, most of the load point EENS have relatively small increases in modification II, when station maintenance outages are considered. It can be seen from Table 4.38 that the system EENS increases slightly by considering station maintenance outages. Tables 4.38 and 4.34 show that modification II provides better reliability than modification I. This modified station configuration is used in later reliability studies.

Selected transmission station modifications

Previous studies show that the EENS indices for the load points at Stations 3, 6, 8, 9, 10 and 19 experience considerable increases by including the effects of station related outages. These transmission stations are possible candidates for modification to improve their reliability levels. Stations 3 and 10 in Figure 4.18 were first modified to one and one half breaker configurations. The configurations of Stations 3 and 10 are shown in Figure 4.20. Station maintenance outages are not considered in this case. Tables 4.39 and 4.40 show the annual load point indices for the IEEE-RTS with and without modifying Stations 3 and 10.

Table 4.39: Annual load point indices without considering maintenance outages for the IEEE-RTS with and without modifying Stations 3 and 10 (Gen. 100% rel.)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (before modification)	Decrease rate (%)
1	29	0.00006	0.03338	2.306	0.00428	37.519	35.098	-6.90
2	34	0.00007	0.05794	3.595	0.00409	35.872	32.611	-10.00
3	35	0.00001	0.08737	10.056	0.00138	12.104	66.567	81.82
4	36	0.00007	0.23417	11.084	0.00350	30.683	34.000	9.76
5	37	0.00008	0.25755	11.696	0.00372	32.622	36.601	10.87
6	38	0.00010	0.33037	28.739	0.00887	77.728	76.204	-2.00
7	39	0.00009	0.11492	9.188	0.00752	65.838	64.437	-2.17
8	43	0.00008	0.09605	10.505	0.00853	74.735	72.819	-2.63
9	44	0.00007	0.13973	15.640	0.00807	70.653	72.615	2.70
10	45	0.00003	0.19852	24.761	0.00374	32.779	96.151	65.91
13	49	0.00008	0.10867	18.420	0.01424	124.727	115.818	-7.69

Table 4.39: (Continued)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (before modification)	Decrease rate (%)
14	50	0.00006	0.18934	23.495	0.00720	63.047	56.525	-11.54
15	51	0.00007	0.08643	17.523	0.01501	131.452	103.033	-27.58
16	59	0.00004	0.05750	3.678	0.00281	24.654	31.378	21.43
18	61	0.00006	0.31740	67.605	0.01321	115.684	111.952	-3.33
19	62	0.00006	0.06490	7.509	0.00651	57.025	65.138	12.46
20	63	0.00005	0.06712	5.496	0.00426	37.295	40.164	7.14

Table 4.40: Annual system indices without considering maintenance outages for the IEEE-RTS with and without modifying Stations 3 and 10 (Gen. 100% rel.)

Indices	Annual	Annual (before modification)
ENLC (1/yr)	2.43949	2.19791
ADLC (hrs/disturbance)	3.95	4.82
EDLC (hrs/yr)	9.640	10.604
PLC	0.00110	0.00121
EDNS (MW)	0.11694	0.12684
EENS (MWh/yr)	1024.42	1111.11
EDC (k$/yr)	4323.04	4688.89
BPII (MW/MW-yr)	0.09519	0.07138
BPECI (MWh/MW-yr)	0.35944	0.38986
BPACI (MW/disturbance)	111.21	92.56
MBECI (MW/MW)	0.00004	0.00004
SI (system minutes/yr)	21.57	23.39

Stations 8 and 19 in addition to Station 3 and 10 are separately modified to one and one half breaker configurations and the system reliability performances are compared for these two cases to determine a possible sequence for system reinforcement.

(a) Subsequent modification - Station 8

Figure 4.20 [28] shows the IEEE-RTS associated with modified Stations 3, 8 and 10. Tables 4.41 and 4.42 show the annual reliability indices for the IEEE-RTS with modified Stations 3 &10 and with and without the modified Station 8. Tables 4.43 and 4.44 show the annual reliability indices without and with station maintenance outages for the IEEE-RTS with modified Stations 3, 8 and 10. The modification of Station 8 affects only its own load point indices.

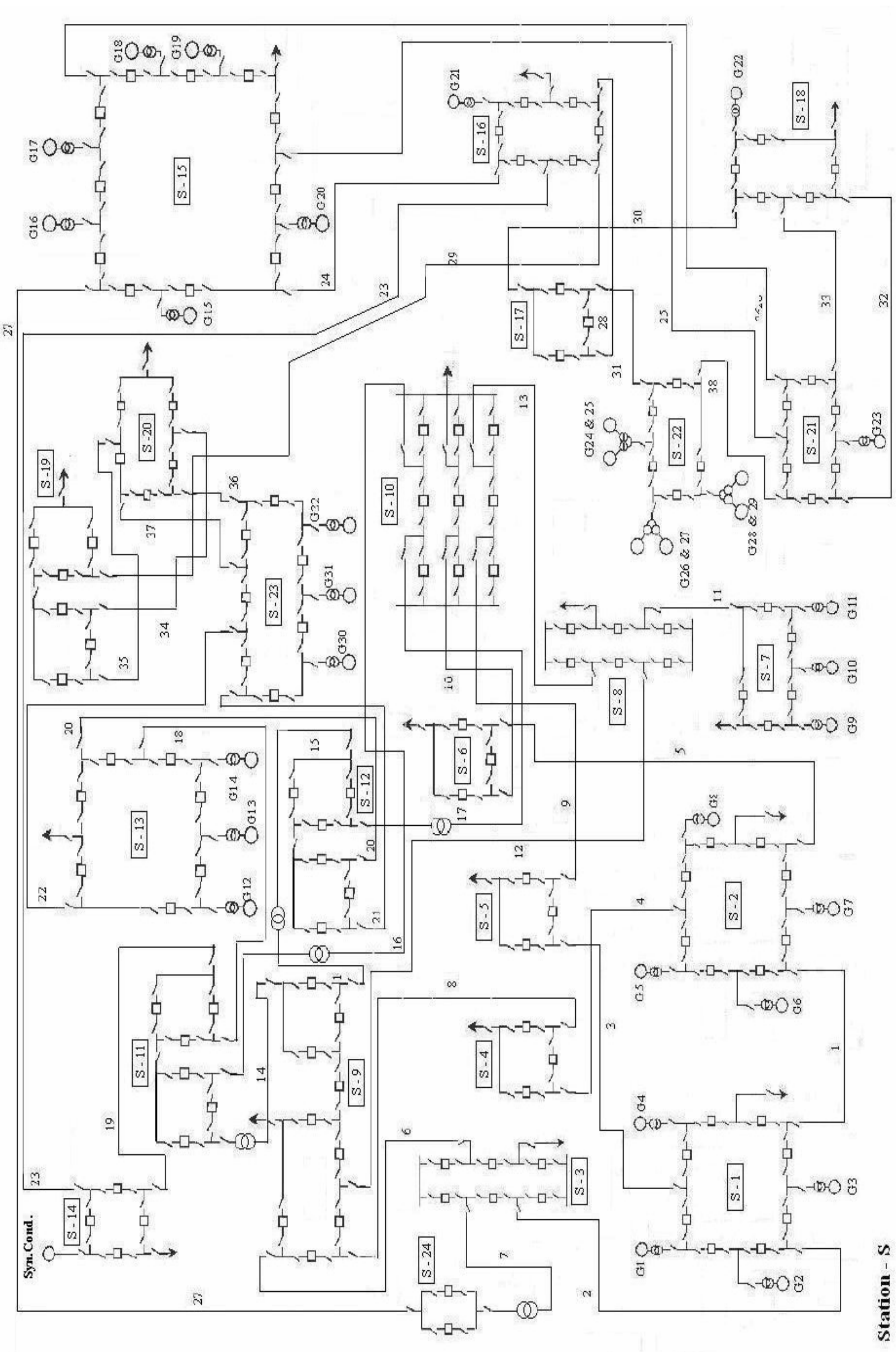

Figure 4.20: IEEE-RTS with modified generating stations 3, 8 and 10

Table 4.41: Annual load point indices without considering maintenance outages for the IEEE-RTS with modified Station 3&10 and with and without modified Station 8 (Gen. 100% rel.)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (before modification)	Decrease rate (%)
1	29	0.00006	0.03340	2.307	0.00428	37.519	37.519	0.00
2	34	0.00007	0.05795	3.596	0.00409	35.872	35.872	0.00
3	35	0.00001	0.08737	10.057	0.00138	12.104	12.104	0.00
4	36	0.00007	0.23419	11.085	0.00350	30.683	30.683	0.00
5	37	0.00008	0.25809	11.721	0.00372	32.622	32.622	0.00
6	38	0.00010	0.33039	28.741	0.00887	77.728	77.728	0.00
7	39	0.00009	0.11494	9.190	0.00752	65.838	65.838	0.00
8	43	0.00002	0.15750	17.227	0.00241	21.079	74.735	71.80
9	44	0.00007	0.13975	15.642	0.00807	70.653	70.653	0.00
10	45	0.00003	0.19852	24.762	0.00374	32.779	32.779	0.00
13	49	0.00008	0.10869	18.424	0.01424	124.727	124.727	0.00
14	50	0.00006	0.18935	23.496	0.00720	63.047	63.047	0.00
15	51	0.00007	0.08644	17.526	0.01501	131.452	131.452	0.00
16	59	0.00004	0.05804	3.713	0.00281	24.654	24.654	0.00
18	61	0.00006	0.31741	67.608	0.01321	115.684	115.684	0.00
19	62	0.00006	0.06491	7.510	0.00651	57.025	57.025	0.00
20	63	0.00005	0.06713	5.496	0.00426	37.295	37.295	0.00

Table 4.42: Annual system indices without considering maintenance outages for the IEEE-RTS with modified Station 3&10 and with and without modified Station 8 (Gen. 100% rel.)

Indices	Annual	Annual (before modification)
ENLC (1/yr)	2.50223	2.43949
ADLC (hrs/disturbance)	3.66	3.95
EDLC (hrs/yr)	9.149	9.640
PLC	0.00104	0.00110
EDNS (MW)	0.11082	0.11694
EENS (MWh/yr)	970.76	1024.42
EDC (k$/yr)	4096.61	4323.04
BPII (MW/MW-yr)	0.09758	0.09519
BPECI (MWh/MW-yr)	0.34062	0.35944
BPACI (MW/disturbance)	111.14	111.21
MBECI (MW/MW)	0.00004	0.00004
SI (system minutes/yr)	20.44	21.57

Table 4.43: Annual load point indices with and without station maintenance outages for the IEEE-RTS with modified Station 3, 8 and 10 (Gen. 100% rel.)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (Table 4.41)	Increase rate (%)
1	29	0.00007	0.06147	4.246	0.00456	39.940	37.519	6.45
2	34	0.00007	0.06538	4.057	0.00434	38.046	35.872	6.06
3	35	0.00002	0.10497	12.082	0.00207	18.156	12.104	50.00
4	36	0.00008	0.23511	11.128	0.00360	31.512	30.683	2.70
5	37	0.00008	0.25800	11.717	0.00372	32.622	32.622	0.00
6	38	0.00010	0.33159	28.845	0.00905	79.252	77.728	1.96
7	39	0.00010	0.11945	9.551	0.00816	71.441	65.838	8.51
8	43	0.00002	0.13560	14.831	0.00241	21.079	21.079	0.00
9	44	0.00007	0.13694	15.323	0.00807	70.728	70.653	0.11
10	45	0.00004	0.18976	23.669	0.00449	39.334	32.779	20.00
13	49	0.00009	0.14212	24.090	0.01526	133.636	124.727	7.14
14	50	0.00006	0.18309	22.719	0.00745	65.221	63.047	3.45
15	51	0.00008	0.08294	16.812	0.01582	138.577	131.452	5.42
16	59	0.00005	0.07606	4.865	0.00320	28.016	24.654	13.64
18	61	0.00007	0.29821	63.518	0.01406	123.147	115.684	6.45
19	62	0.00007	0.06956	8.024	0.00770	67.484	57.025	18.34
20	63	0.00005	0.08324	6.815	0.00442	38.729	37.295	3.85

Table 4.44: Annual system indices with and without station maintenance outages for the IEEE-RTS with modified Station 3, 8 and 10 (Gen. 100% rel.)

Indices	Annual	Annual (Table 4.42)
ENLC (1/yr)	2.57155	2.50223
ADLC (hrs/disturbance)	3.78	3.66
EDLC (hrs/yr)	9.732	9.149
PLC	0.00111	0.00104
EDNS (MW)	0.11837	0.11082
EENS (MWh/yr)	1036.92	970.76
EDC (k$/yr)	4375.81	4096.61
BPII (MW/MW-yr)	0.09905	0.09758
BPECI (MWh/MW-yr)	0.36383	0.34062
BPACI (MW/disturbance)	109.76	111.14
MBECI (MW/MW)	0.00004	0.00004
SI (system minutes/yr)	21.83	20.44

The load point and system EENS increase at different rates by incorporating station maintenance outages. The increased rates in the load point EENS at Stations 3 and 10 are larger than those at the other stations as their load point EENS decreased considerably after modification.

(b) Subsequent modification- Station 19

Modified Station 19 is shown in Figure D.2 (Appendix D). Tables 4.45 and 4.46 show the reliability indices for the IEEE-RTS with and without modifying Stations 3, 10 and 19. Station maintenance outages are not included in this case.

Table 4.45: Annual load point indices without considering maintenance outages for the IEEE-RTS with modified Station 3&10 and with and without modified Station 19 (Gen. 100% rel.)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (before modification)	Decrease rate (%)
1	29	0.00006	0.03340	2.308	0.00428	37.519	37.519	0.00
2	34	0.00007	0.05796	3.596	0.00409	35.872	35.872	0.00
3	35	0.00001	0.08737	10.057	0.00138	12.104	12.104	0.00
4	36	0.00007	0.23420	11.085	0.00350	30.683	30.683	0.00
5	37	0.00008	0.25758	11.698	0.00372	32.622	32.622	0.00
6	38	0.00010	0.33040	28.742	0.00887	77.728	77.728	0.00
7	39	0.00009	0.11598	9.273	0.00752	65.838	65.838	0.00
8	43	0.00008	0.09608	10.509	0.00853	74.735	74.735	0.00
9	44	0.00007	0.13976	15.643	0.00807	70.653	70.653	0.00
10	45	0.00003	0.19853	24.762	0.00374	32.779	32.779	0.00
13	49	0.00008	0.10870	18.426	0.01424	124.727	124.727	0.00
14	50	0.00006	0.18936	23.497	0.00720	63.047	63.047	0.00
15	51	0.00007	0.08645	17.528	0.01501	131.452	131.452	0.00
16	59	0.00004	0.05752	3.679	0.00281	24.654	24.654	0.00
18	61	0.00006	0.31742	67.610	0.01321	115.684	115.684	0.00
19	62	0.00002	0.18025	20.863	0.00280	24.571	57.025	56.91
20	63	0.00005	0.07171	5.871	0.00426	37.295	37.295	0.00

Table 4.46: Annual system indices without considering maintenance outages for the IEEE-RTS with modified Station 3&10 and with and without modified Station 19 (Gen. 100% rel.)

Indices	Annual	Annual (before modification)
ENLC (1/yr)	2.56081	2.43949
ADLC (hrs/disturbance)	3.65	3.95
EDLC (hrs/yr)	9.359	9.640
PLC	0.00107	0.00110
EDNS (MW)	0.11324	0.11694
EENS (MWh/yr)	991.96	1024.42
EDC (k$/yr)	4186.08	4323.04
BPII (MW/MW-yr)	0.10005	0.09519
BPECI (MWh/MW-yr)	0.34806	0.35944
BPACI (MW/disturbance)	111.35	111.21
MBECI (MW/MW)	0.00004	0.00004
SI (system minutes/yr)	20.88	21.57

The system EENS for the IEEE-RTS with modified Stations 3, 8 and 10 is a little lower than that for the IEEE-RTS with modified Stations 3, 10 and 19. The load point at Station 19 has the lowest economic priority order in the IEEE-RTS. It would therefore be logical to select Station 8 to be modified to a one and one half breaker configuration before Station 19.

4.4.3 Base Case Analysis for the IEEE-RTS with Mixed Station Configurations

A series of station modifications are analyzed in the previous section. Generation and transmission station modifications were analyzed separately in these studies. In this section, generating stations 13, 15 and 18 and transmission stations 3, 8 and 10 are modified simultaneously to one and one half breaker configurations in order to improve the reliability performance of the IEEE-RTS. This IEEE-RTS with mixed ring bus and one and one half breaker schemes is shown in Figure 4.21 [28]. The reliability indices without and with station maintenance outages for the modified IEEE-RTS are evaluated and shown in the following. The reliability studies were conducted assuming that the generators are and are not 100% reliable.

Analysis of the IEEE-RTS with mixed station schemes (generators are 100% reliable)

The reliability indices for the IEEE-RTS with mixed station configurations and with ring bus configurations are shown in Tables 4.47 and 4.48 respectively. The reliability indices with and without station maintenance outages for the IEEE-RTS with mixed station configurations are shown in Tables 4.49 and 4.50 respectively.

It can be seen from Table 4.47 that the load point EENS at the six selected stations decrease significantly for the IEEE-RTS with mixed station configurations. The load point EENS at some other stations decreases while that at a few stations increases. The modified IEEE-RTS is more reliable as the system EENS is much lower than that of the IEEE-RTS with ring bus configurations.

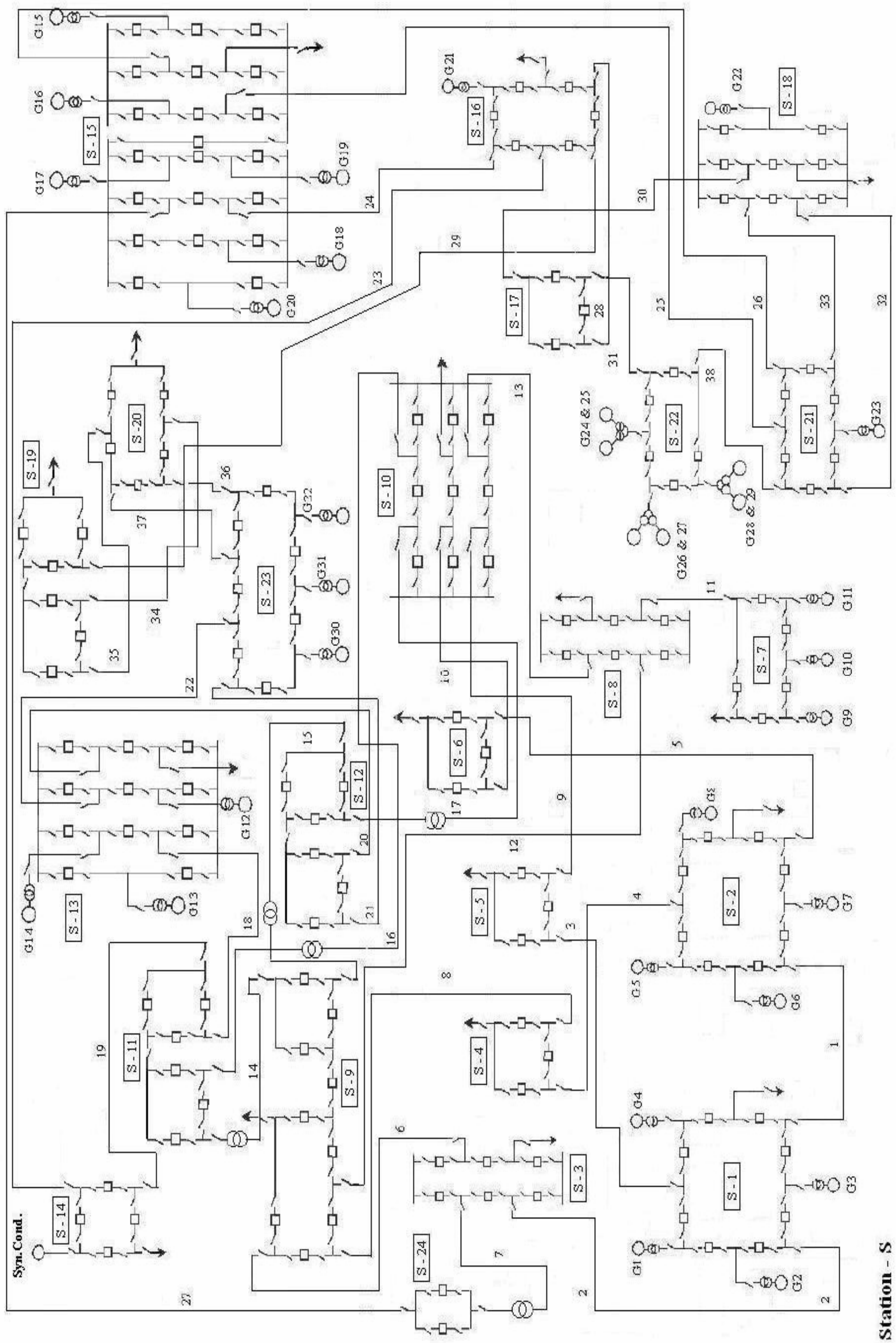

Figure 4.21: IEEE-RTS with mixed ring bus and one and one half breaker configurations

Table 4.47: Annual load point indices without considering station maintenance outages for the IEEE-RTS with mixed station schemes and with ring bus schemes (Gen. 100% rel.)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (ring configuration)	Decrease rate (%)
1	29	0.00006	0.04671	3.234	0.00442	38.729	35.098	-10.35
2	34	0.00007	0.04450	2.767	0.00409	35.872	32.611	-10.00
3	35	0.00001	0.08740	10.060	0.00138	12.104	66.567	81.82
4	36	0.00007	0.23438	11.094	0.00350	30.683	34.000	9.76
5	37	0.00008	0.25831	11.731	0.00372	32.622	36.601	10.87
6	38	0.00010	0.33074	28.771	0.00887	77.728	76.204	-2.00
7	39	0.00010	0.11923	9.533	0.00816	71.441	64.437	-10.87
8	43	0.00002	0.15764	17.242	0.00241	21.079	72.819	71.05
9	44	0.00007	0.12708	14.224	0.00807	70.653	72.615	2.70
10	45	0.00003	0.19868	24.782	0.00374	32.779	96.151	65.91
13	49	0.00003	0.22007	37.302	0.00509	44.545	115.818	61.54
14	50	0.00005	0.15006	18.621	0.00620	54.351	56.525	3.85
15	51	0.00002	0.17995	36.486	0.00487	42.641	103.033	58.61
16	59	0.00006	0.13932	8.911	0.00409	35.860	31.378	-14.28
18	61	0.00003	0.19164	40.819	0.00554	48.513	111.952	56.67
19	62	0.00004	0.06252	7.233	0.00512	44.852	65.138	31.14
20	63	0.00006	0.11709	9.586	0.00524	45.901	40.164	-14.28

Table 4.48: Annual system indices without considering station maintenance outages for the IEEE-RTS with mixed station schemes and with ring bus schemes (Gen. 100% rel.)

Indices	Annual	Annual (ring configuration)
ENLC (1/yr)	2.66347	2.19791
ADLC (hrs/disturbance)	3.05	4.82
EDLC (hrs/yr)	8.115	10.604
PLC	0.00093	0.00121
EDNS (MW)	0.08452	0.12684
EENS (MWh/yr)	740.35	1111.11
EDC (k$/yr)	3124.30	4688.89
BPII (MW/MW-yr)	0.10259	0.07138
BPECI (MWh/MW-yr)	0.25977	0.38986
BPACI (MW/disturbance)	109.78	92.56
MBECI (MW/MW)	0.00003	0.00004
SI (system minutes/yr)	15.59	23.39

Table 4.49: Annual load point indices with and without station maintenance outages for the IEEE-RTS with mixed station scheme (Gen. 100% rel.)

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (Table 4.47)	Increase rate (%)
1	29	0.00007	0.06388	4.413	0.00484	42.360	38.729	9.38
2	34	0.00007	0.05580	3.462	0.00447	39.133	35.872	9.09
3	35	0.00002	0.10502	12.087	0.00207	18.156	12.104	50.00
4	36	0.00008	0.23541	11.143	0.00360	31.512	30.683	2.70
5	37	0.00008	0.25822	11.727	0.00372	32.622	32.622	0.00
6	38	0.00010	0.33201	28.882	0.00905	79.252	77.728	1.96
7	39	0.00011	0.12346	9.871	0.00879	77.044	71.441	7.84
8	43	0.00002	0.13570	14.843	0.00241	21.079	21.079	0.00
9	44	0.00007	0.12414	13.890	0.00807	70.728	70.653	0.10
10	45	0.00004	0.18991	23.687	0.00449	39.334	32.779	20.00
13	49	0.00003	0.18557	31.455	0.00509	44.545	44.545	0.00
14	50	0.00005	0.14500	17.993	0.00645	56.525	54.351	4.00
15	51	0.00003	0.16156	32.753	0.00528	46.214	42.641	8.38
16	59	0.00007	0.14263	9.123	0.00448	39.222	35.860	9.38
18	61	0.00003	0.18200	38.776	0.00639	55.976	48.513	15.38
19	62	0.00005	0.11281	13.034	0.00631	55.312	44.852	23.31
20	63	0.00007	0.13316	10.902	0.00540	47.336	45.901	3.13

Table 4.50: Annual system indices with and without station maintenance outages for the modified IEEE-RTS with mixed station scheme (Gen. 100% rel.)

Indices	Annual	Annual (Table 4.48)
ENLC (1/yr)	2.68443	2.66347
ADLC (hrs/disturbance)	3.23	3.05
EDLC (hrs/yr)	8.663	8.115
PLC	0.00099	0.00093
EDNS (MW)	0.09091	0.08452
EENS (MWh/yr)	796.35	740.35
EDC (k$/yr)	3360.60	3124.30
BPII (MW/MW-yr)	0.10107	0.10259
BPECI (MWh/MW-yr)	0.279	0.25977
BPACI (MW/disturbance)	107.30	109.78
MBECI (MW/MW)	0.00003	0.00003
SI (system minutes/yr)	16.77	15.59

The load point and system EENS comparisons of the IEEE-RTS with ring bus schemes and with mixed station schemes assuming the generators to be 100% reliable are shown in Table 4.51. Station maintenance outages are included. It can be seen that the load point EENS at most of the stations decrease with different rates for the IEEE-RTS with mixed station schemes, compared to those for the IEEE-RTS with ring bus schemes. The system EENS decreases significantly for the IEEE-RTS with mixed station schemes. The system becomes considerably more reliable when the six selected stations are modified to one and one half breaker schemes.

Table 4.51: Load point and system EENS comparison between the IEEE-RTS with ring bus schemes and with mixed station schemes (Gen. 100% rel.)

Station No.	Bus No.	EENS (ring configuration)	EENS (MWh/yr)	Decrease rate (%)
1	29	38.729	42.360	-9.38
2	34	35.872	39.133	-9.09
3	35	70.602	18.156	74.28
4	36	34.829	31.512	9.52
5	37	36.601	32.622	10.87
6	38	77.728	79.252	-1.96
7	39	70.040	77.044	-10.00
8	43	76.652	21.079	72.50
9	44	72.695	70.728	2.71
10	45	107.077	39.334	63.27
13	49	124.727	44.545	64.29
14	50	58.699	56.525	3.70
15	51	117.265	46.214	60.59
16	59	34.740	39.222	-12.90
18	61	119.415	55.976	53.12
19	62	75.613	55.312	26.85
20	63	41.598	47.336	-13.79
System		1192.882	796.351	33.24

Analysis of the IEEE-RTS with mixed station schemes (generators are not 100% reliable)

The modified generator reliability data of the IEEE-RTS are given in Table A.11. The modified data for the transmission lines, transformers and equivalent load circuits without and with station related maintenance outages for the IEEE-RTS with mixed station schemes are presented in Tables D.3 and D.4 respectively.

The annual load point and system reliability indices for the IEEE-RTS with mixed station configurations are shown in Tables 4.52 and 4.53 respectively. The annual reliability indices with and without station maintenance outages for the IEEE-RTS with mixed station schemes are shown in Tables 4.54 and 4.55 respectively.

Table 4.52: Annual load point indices for the IEEE-RTS with mixed ring bus and one and one half breaker schemes

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)
1	29	0.00006	0.22034	15.221	0.00442	38.729
2	34	0.00007	0.16164	9.994	0.00413	36.171
3	35	0.00001	0.09793	11.207	0.00140	12.258
4	36	0.00007	0.27048	12.803	0.00350	30.683
5	37	0.00008	0.30021	13.634	0.00372	32.622
6	38	0.00010	0.37979	33.038	0.00887	77.728
7	39	0.00010	0.27346	21.864	0.00816	71.441
8	43	0.00002	0.17643	19.292	0.00241	21.081
9	44	0.00119	1.16952	82.250	0.07704	674.855
10	45	0.00003	0.23001	28.292	0.00398	34.832
13	49	0.00003	0.23845	40.405	0.00509	44.566
14	50	0.00026	0.38076	34.892	0.01848	161.922
15	51	0.00068	0.77877	90.318	0.06026	527.905
16	59	0.00016	0.44385	26.040	0.00757	66.293
18	61	0.00006	0.31479	62.608	0.00953	83.479
19	62	0.00204	1.91543	132.959	0.13255	1161.162
20	63	0.00012	0.37185	28.196	0.00776	67.982

Table 4.53: Annual system indices for the IEEE-RTS with mixed ring bus and one and one half breaker schemes

Indices	Annual
ENLC (1/yr)	5.77890
ADLC (hrs/disturbance)	4.44202
EDLC (hrs/yr)	25.67
PLC	0.00293
EDNS (MW)	0.35887
EENS (MWh/yr)	3143.71
EDC (k$/yr)	13266.44
BPII (MW/MW-yr)	0.232
BPECI (MWh/MW-yr)	1.103
BPACI (MW/disturbance)	114.731
MBECI (MW/MW)	0.00013
SI (system minutes/yr)	66.18

Table 4.54: Annual load point indices with and without station maintenance outages for the IEEE-RTS with mixed station configurations

Station No.	Bus No.	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWh/yr)	EENS (Table 4.52)	Increase rate (%)
1	29	0.00007	0.21834	15.083	0.00484	42.360	38.729	9.38
2	34	0.00007	0.15636	9.657	0.00451	39.495	36.171	9.19
3	35	0.00002	0.12443	14.244	0.00210	18.373	12.258	49.89
4	36	0.00008	0.27285	12.915	0.00360	31.512	30.683	2.70
5	37	0.00008	0.30009	13.628	0.00372	32.622	32.622	0.00
6	38	0.00010	0.38157	33.193	0.00905	79.252	77.728	1.96
7	39	0.00011	0.27411	21.916	0.00879	77.044	71.441	7.84
8	43	0.00002	0.16059	17.559	0.00241	21.082	21.081	0.00
9	44	0.00127	1.24988	87.009	0.08180	716.533	674.855	6.18
10	45	0.00004	0.23402	28.746	0.00477	41.754	34.832	19.87
13	49	0.00003	0.20671	35.021	0.00509	44.584	44.566	0.04
14	50	0.00027	0.39459	35.561	0.01980	173.422	161.922	7.10
15	51	0.00073	0.81969	93.017	0.06484	568.037	527.905	7.60
16	59	0.00017	0.46011	26.817	0.00826	72.370	66.293	9.17
18	61	0.00007	0.31748	62.602	0.01066	93.348	83.479	11.82
19	62	0.00218	2.06339	142.864	0.14178	1241.966	1161.162	6.96
20	63	0.00013	0.38033	28.684	0.00819	71.711	67.982	5.49

Table 4.55: Annual system indices with and without station maintenance outages for the IEEE-RTS with mixed station configurations

Indices	Annual	Annual (Table 4.53)
ENLC (1/yr)	5.89811	5.77890
ADLC (hrs/disturbance)	4.63532	4.44202
EDLC (hrs/yr)	27.34	25.67
PLC	0.00312	0.00293
EDNS (MW)	0.38418	0.35887
EENS (MWh/yr)	3365.46	3143.71
EDC (k$/yr)	14202.24	13266.44
BPII (MW/MW-yr)	0.238	0.232
BPECI (MWh/MW-yr)	1.181	1.103
BPACI (MW/disturbance)	115.05	114.731
MBECI (MW/MW)	0.00013	0.00013
SI (system minutes/yr)	70.85	66.18

Tables 4.54 and 4.55 show that the load point and system EENS increase at different rates by incorporating station maintenance outages.

4.4.4 Reliability Comparison of the IEEE-RTS with Ring Bus and with Mixed Station Configurations

Six stations including generating stations 13, 15 and 18 and transmission stations 3, 8 and 10 were selected to be modified simultaneously to improve the IEEE-RTS reliability. The reliability performances are compared in this section for the IEEE-RTS with ring bus schemes and with mixed ring bus and one and one half breaker schemes. The load point and system EENS comparison without and with station maintenance outages for the IEEE-RTS with ring bus schemes and with mixed station schemes are shown in Tables 4.56 and 4.57 respectively.

Table 4.56: Load point and system EENS comparison for the IEEE-RTS with ring bus schemes and with mixed station schemes (without considering station maintenance outages)

Station No.	Bus No.	EENS (MWh/yr) (Ring)	EENS (MWh/yr) (Mixed)	Decrease rate (%)
1	29	35.098	38.729	-10.35
2	34	32.902	36.171	-9.94
3	35	66.718	12.258	81.63
4	36	34.000	30.683	9.76
5	37	36.601	32.622	10.87
6	38	76.204	77.728	-2.00
7	39	64.437	71.441	-10.87
8	43	72.822	21.081	71.05
9	44	677.362	674.855	0.37
10	45	98.168	34.832	64.52
13	49	115.839	44.566	61.53
14	50	164.168	161.922	1.37
15	51	588.760	527.905	10.34
16	59	61.758	66.293	-7.34
18	61	131.837	83.479	36.68
19	62	1182.313	1161.162	1.79
20	63	62.225	67.982	-9.25
System		3501.210	3143.710	10.21

Ring – ring bus schemes, Mixed – mixed station schemes

Table 4.57: Load point and system EENS comparison for the IEEE-RTS with ring bus schemes and with mixed station schemes (considering station maintenance outages)

Station No.	Bus No.	EENS (MWh/yr) (Ring)	EENS (MWh/yr) (Mixed)	Decrease rate (%)
1	29	38.729	42.360	-9.38
2	34	36.225	39.495	-9.03
3	35	70.816	18.373	74.06
4	36	34.829	31.512	9.52
5	37	36.601	32.622	10.87
6	38	77.728	79.252	-1.96
7	39	70.040	77.044	-10.00
8	43	76.655	21.082	72.50
9	44	718.873	716.533	0.33
10	45	109.460	41.754	61.85
13	49	124.765	44.584	64.27
14	50	175.650	173.422	1.27
15	51	639.453	568.037	11.17
16	59	67.833	72.370	-6.69
18	61	145.437	93.348	35.82
19	62	1263.000	1241.966	1.67
20	63	65.952	71.711	-8.73
System		3752.043	3365.459	10.30

Ring – ring bus schemes, Mixed – mixed station schemes

It can be seen from Tables 4.56 and 4.57 that the load point EENS at each station change at different rates after the six stations are modified to one and one half breaker configurations. The load point EENS at the six selected stations have higher decreases than those at the other stations. The variations in the all load point EENS are similar to those in Table 4.47 in which all the generators are 100% reliable. The system EENS of the IEEE-RTS with mixed ring bus and one and one half breaker schemes is much smaller than that of the IEEE-RTS with ring bus schemes. The system is comparatively reliable after the six selected stations are modified to one and one half breaker schemes.

Figures 4.22 and 4.23 show the load point EENS comparison without and with station maintenance outages for the IEEE-RTS with three different schemes. These schemes are without considering station effects (base case reliability indices in Tables 2.18 and 2.19), with ring bus schemes and with mixed station schemes.

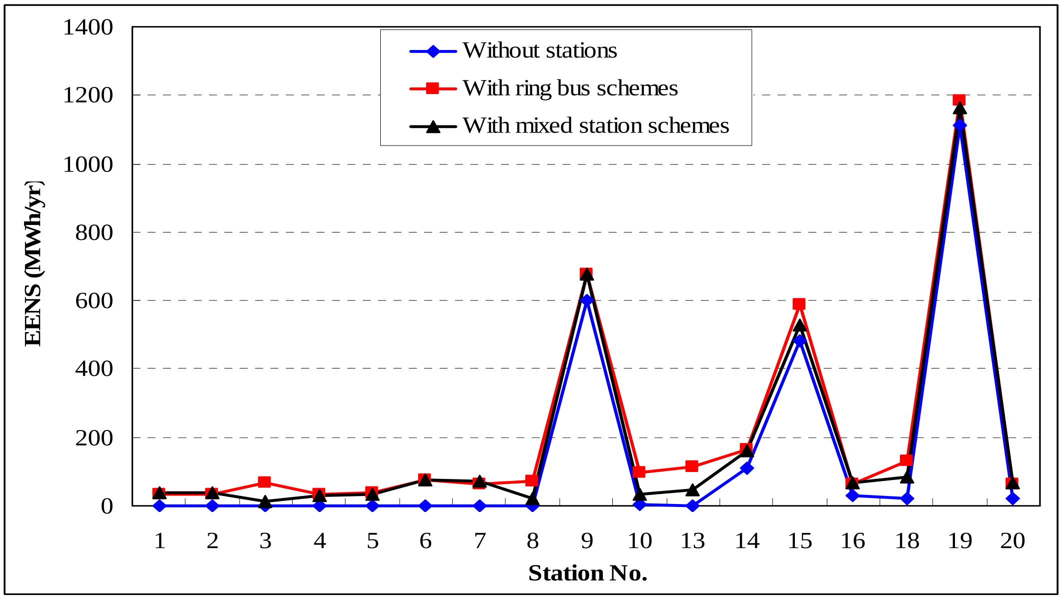

Figure 4.22: Load point reliability comparison for the IEEE-RTS with three different schemes (without considering station maintenance outages)

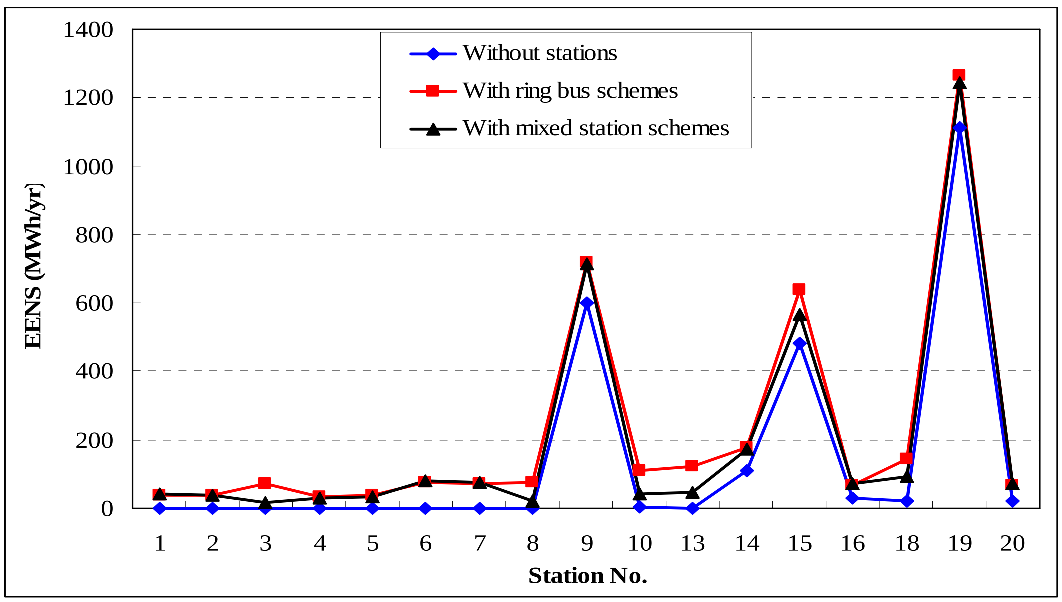

Figure 4.23: Load point reliability comparison for the IEEE-RTS with three different schemes (considering station maintenance outages)

It can be seen from Figures 4.22 and 4.23 that the load point EENS increase at different levels when station related outages are incorporated. The load point EENS at the six selected stations have comparatively large decreases for the IEEE-RTS with mixed station schemes when compared with those for the IEEE-RTS with ring bus schemes, whether station related maintenance outages are included or not.

The results also show that not considering station related maintenance outages underestimates the effects of station related outages on composite system reliability performance. This could lead to improper decisions in the station planning and design process. This is illustrated in this chapter using Station 13 in the IEEE-RTS. The impact on the EENS of modifying the station topology is illustrated together with the changes in the contribution due to incorporating maintenance outages in the evaluation.

4.5 Summary

In this chapter, station related maintenance outages are incorporated in the reliability evaluation of two composite test systems, the RBTS and the IEEE-RTS. The load point and system reliability indices are evaluated and compared for the RBTS and the modified RBTS with four different station configurations. These are ring bus, double bus double breaker, one and one half breaker and one and one third breaker configurations. Reliability indices of the IEEE-RTS with ring bus configurations and with mixed station configurations are analyzed respectively and compared in this chapter. The results show that the load point and system EENS increase at different rates by incorporating station related maintenance outages in the composite system reliability evaluation.

Reliability analyses for the RBTS with the four different station schemes show that the RBTS with double bus double breaker schemes has the lowest system EENS and thus is the most reliable system and the one with ring bus stations is the least reliable. The RBTS with double bus double breaker configurations, however, is the most expensive and requires the most equipment. The studies also show that the configuration used at Station 6 has a large impact on the load point and system indices.

The load point and system reliability indices are dominated by the Station 6 values due to the radial line supply to this bus. The original RBTS was modified by removing the radial line supplying Bus 6 and including this load at Bus 5 in order to focus on the effects of station related maintenance outages. Reliability studies on the modified RBTS with the four different station schemes show that the RBTS with ring bus stations is the least reliable system. The reliability indices of EENS and SI for the modified RBTS with double bus double breaker schemes, one and one half breaker schemes and one and one third breaker schemes are very similar, whether station related maintenance outages are incorporated or not. This may not be the case when the station component reliability data changes.

Station maintenance outages are incorporated in the reliability evaluation of the IEEE-RTS with ring bus schemes. Six stations were selected to be modified to one and one half breaker schemes in order to improve the IEEE-RTS reliability. The reliability indices without and with station maintenance outages for the IEEE-RTS with mixed ring bus and one and one half breaker schemes are evaluated. The results show that the load point EENS at the modified stations have meaningful decreases for the IEEE-RTS with mixed station schemes compared to those for the IEEE-RTS with ring bus schemes, whether station related maintenance outages are included or not. The predicted composite system reliability performance becomes worse as station maintenance outages are incorporated.

The studies in this chapter show that it is important and necessary to incorporate station related maintenance outages in composite system reliability evaluation. Probabilistic analyses not considering station related maintenance outage underestimates the effects of station related outages on composite system reliability performance. This could lead to improper decisions in the station planning, design and operation process. This is illustrated in this chapter using Station 13 in the IEEE-RTS. The impact on the EENS of modifying the station topology is illustrated together with the changes in the contribution due to incorporating maintenance outages in the evaluation.

The purpose of preventive maintenance is to increase the useful equipment life and thus improve equipment and system reliability. In the analyses described in this chapter, the assumption is made that maintenance is necessary to keep the equipment failure rates constant at the assigned values. The removal of equipment for maintenance, therefore creates a more vulnerable system and increases in the predicted EENS. The effects of increased failure rates due to equipment deterioration are discussed in Chapter 6. The impacts of component parameter variations on the load point and system reliability incorporating maintenance outages are presented in the next chapter.

Chapter 5

Composite System Reliability Sensitivity Analysis

5.1 Introduction

Station related maintenance outages have been incorporated in the reliability evaluation of the two composite test systems and the results indicate that the predicted reliability indices increase noticeably due to the enhanced risk of load point and system failures during the maintenance activities. The reliability studies were concentrated on the impacts of station related maintenance outages during the useful life of system equipment in which component failure rates are assumed to be constant. In an actual power system, electric equipment continues to age year by year. The bulk of the existing infrastructure of most electric power systems has been installed over the last 30 to 50 years [4]. From a reliability point of view, equipment aging results in increasing component failure rates. It is therefore important and necessary to appreciate the effects on composite system reliability of variations in station component reliability data.

The load point and system reliability of a composite system is a function of the reliability of the individual station components and the station configurations. Individual component reliability is expressed by the failure rate, repair rate, maintenance outage rate and maintenance duration rate. Reliability parameters such as the failure rate, repair rate and maintenance rate can change over the component life cycle. The component failure rate is affected by a series of factors, such as preventive maintenance practices, its designed useful life and variations in the environment. The failure rates of electric equipment increase as they wear out. Component repair rates, however, are influenced by repair strategies, manpower and so on and variations in these parameters are not considered in this research work. Electric power companies establish preventive maintenance policies to keep components in good operation and prolong their useful lives. Component maintenance rates can also change due to adjustments in the maintenance strategies. Too little maintenance may result in an increasing number of component failures and poor component and system reliability. On the other hand, too frequent maintenance may improve the component reliability but the cost of maintenance will greatly increase. In this section, the effects on composite system reliability of variations in the failure rates of circuit breakers and bus bars, and circuit breaker maintenance rates are investigated.

Sensitivity analyses are presented in this chapter to illustrate how variations in the station component reliability data affect the reliability indices of the two composite test systems. The EENS index is an important reliability indicator and is used to represent and compare the reliability performance of the composite system with alternative station schemes. The sensitivity studies are first conducted on the modified RBTS with ring bus, double bus double breaker, one and one half breaker and one and one third breaker schemes respectively and then the results for the modified RBTS with the four station schemes are compared. The analyses conducted on the IEEE-RTS are done with ring bus configurations and mixed station configurations.

5.2 Sensitivity Analyses of the Modified RBTS with the Four Different Station Configurations

The modified RBTS shown in Section 4.3.2 is used in the following sensitivity studies in order to focus on the effects of station maintenance outages. Four different station schemes are incorporated in the modified RBTS. These are ring bus, double bus double breaker, one and one half breaker and one and one third breaker configurations. The effects of variations in the failure and maintenance rates of circuit breakers and bus bars on the load point and system reliability for the modified RBTS with the four different station schemes are investigated. The load point and system EENS are used to quantify the reliability.

5.2.1 Sensitivity Analyses of the Modified RBTS with Ring Bus Configurations

The single line diagram of the modified RBTS with ring bus schemes is shown in Figure 4.11. Tables 5.1 and 5.2 show the system EENS without and with station maintenance outages as a function of the circuit breaker and bus bar failure rates respectively. The relative impacts of station maintenance outages on the system EENS become larger with increase in the circuit breaker failure rates, and decrease with increase in the bus bar failure rates. This is because the system EENS is more sensitive to increase in the bus bar failure rates than in the circuit breaker failure rates.

Table 5.1: System EENS without and with station maintenance outages as a function of the circuit breaker failure rates for the modified RBTS with ring bus schemes

Circuit breaker failure rate multiplier	EENS (without maintenance)	EENS (including maintenance)	Increase rate (%)
1	50.52851	55.57458	9.99
10	74.75841	82.65248	10.56
20	104.41490	118.24577	13.25

Table 5.2: System EENS without and with station maintenance outages as a function of the bus bar failure rates for the modified RBTS with ring bus schemes

Bus bar failure rate multiplier	EENS (without maintenance)	EENS (including maintenance)	Increase rate (%)
1	50.52851	55.57458	9.99
10	315.07796	321.47035	2.03
20	620.92322	631.11442	1.64

The EENS as a function of the circuit breaker failure rates, bus bar failure rates and circuit breaker maintenance rates are shown in Figures 5.1-5.6. Station maintenance outages are included in these analyses.

Reliability as a function of the circuit breaker failure rates

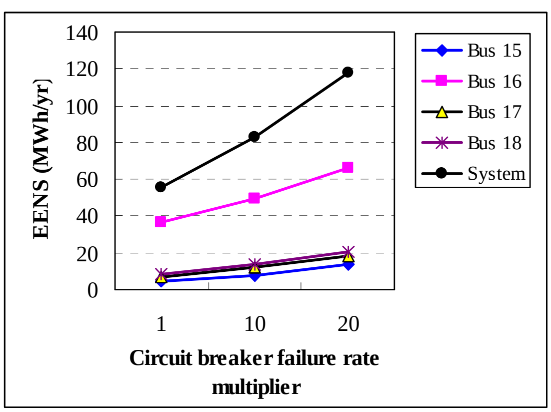

Figure 5.1: Load point and system EENS versus the circuit breaker failure rate multiplier for the modified RBTS with ring bus schemes

Reliability as a function of the bus bar failure rates

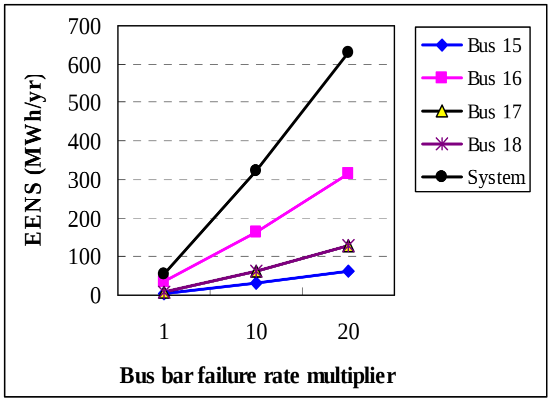

Figure 5.2: Load point and system EENS versus the bus bar failure rate multiplier for the modified RBTS with ring bus schemes

Reliability as a function of the circuit breaker maintenance rates

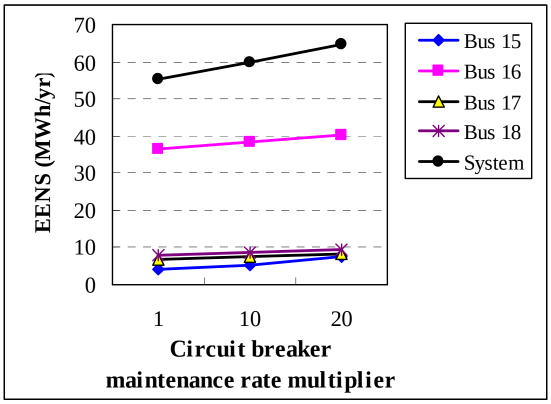

Figure 5.3: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with ring bus schemes

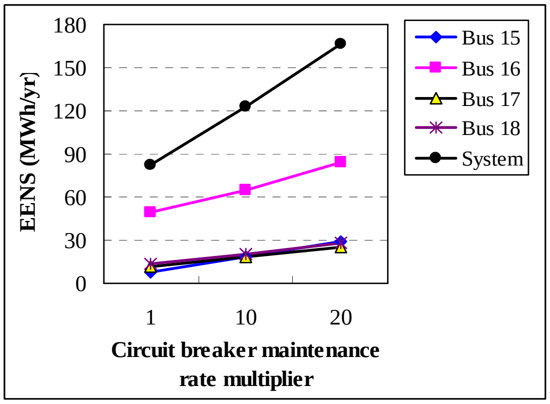

Figure 5.4: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with ring bus schemes (Circuit breaker failure rates increased 10 times)

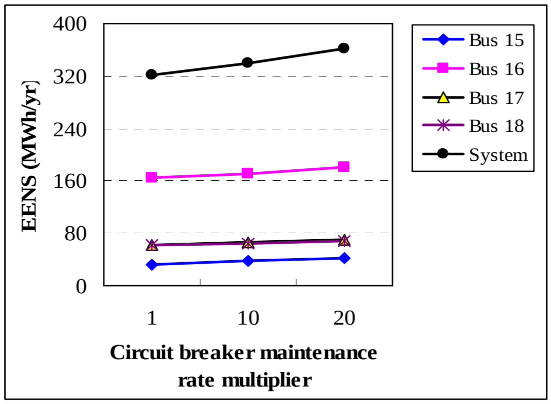

Figure 5.5: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with ring bus schemes (Bus bar failure rates increased 10 times)

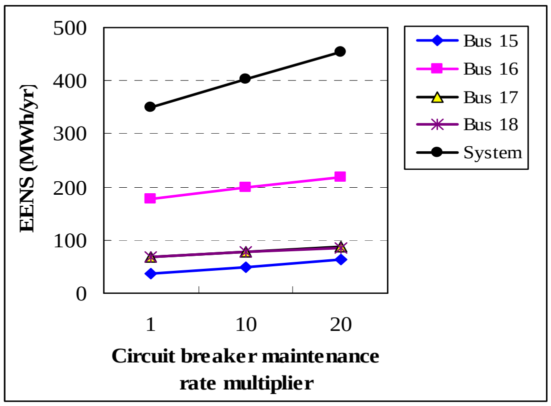

Figure 5.6: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with ring bus schemes (Circuit breaker and bus bar failure rates increased 10 times)

The results show that the load point and system EENS increase as the circuit breaker failure rates, circuit breaker maintenance rates or bus bar failure rates increase while the impacts of their variations are different. Comparing the results, the reliability indices for the modified RBTS with ring bus schemes are more sensitive to variations in the bus bar failure rates than to variations in the circuit breaker failure rates. Circuit breaker maintenance rates have relatively small effects on the load point and system indices compared with circuit breaker failure rates. The effects of circuit breaker maintenance rates become larger with increase in the failure rates of circuit breakers or bus bars, particularly when the failure rates of circuit breakers and bus bars increase simultaneously. The analysis illustrates that the effects of removing circuit breakers from service for maintenance increase as station components age.

5.2.2 Sensitivity Analyses of the Modified RBTS with Double Bus Double Breaker Configurations

The single line diagram of the modified RBTS with double bus double breaker schemes is shown in Figure 4.12. Tables 5.3 and 5.4 show the system EENS without and with station maintenance outages as a function of the circuit breaker and bus bar failure rate respectively.

The effects of station maintenance outages on the system EENS decrease with increase in the circuit breaker failure rates, and increase with increase in the bus bar failure rates. This is because the system EENS in this case is more sensitive to the increase in the circuit breaker failure rates than in the bus bar failure rates.

Table 5.3: System EENS without and with station maintenance outages as a function of the circuit breaker failure rates for the modified RBTS with double bus double breaker schemes

Circuit breaker failure rate multiplier	EENS (without maintenance)	EENS (including maintenance)	Increase rate (%)
1	22.38032	28.13848	25.73
10	44.49847	52.35716	17.66
20	69.76162	81.16358	16.34

Table 5.4: System EENS without and with station maintenance outages as a function of the bus bar failure rates for the modified RBTS with double bus double breaker schemes

Bus bar failure rate multiplier	EENS (without maintenance)	EENS (including maintenance)	Increase rate (%)
1	22.38032	28.13848	25.73
10	22.38032	29.23116	30.61
20	22.38032	29.75073	32.93

The EENS as a function of the circuit breaker failure rates, bus bar failure rates and circuit breaker maintenance rates are shown in Figures 5.7-5.12. Station maintenance outages are included in these analyses.

Reliability as a function of the circuit breaker failure rates

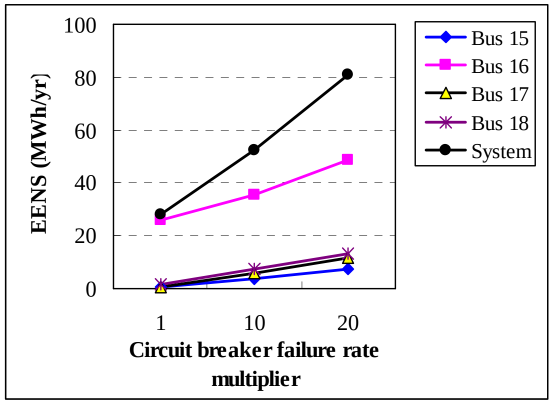

Figure 5.7: Load point and system EENS versus the circuit breaker failure rate multiplier for the modified RBTS with double bus double breaker schemes

Reliability as a function of the bus bar failure rates

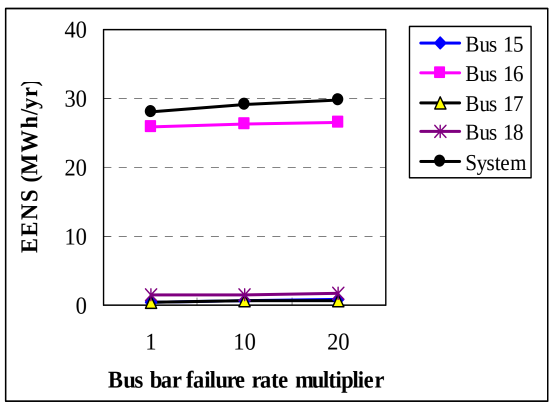

Figure 5.8: Load point and system EENS versus the bus bar failure rate multiplier for the modified RBTS with double bus double breaker schemes

Reliability as a function of the circuit breaker maintenance rates

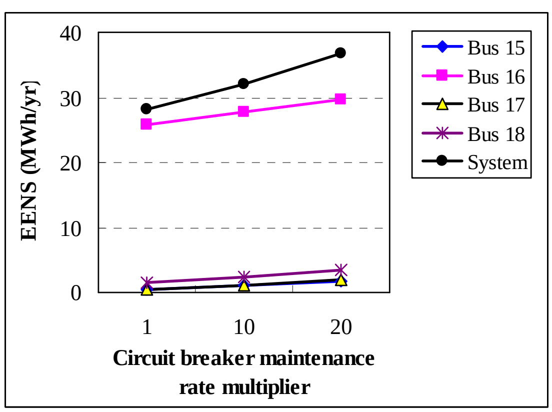

Figure 5.9: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with double bus double breaker schemes

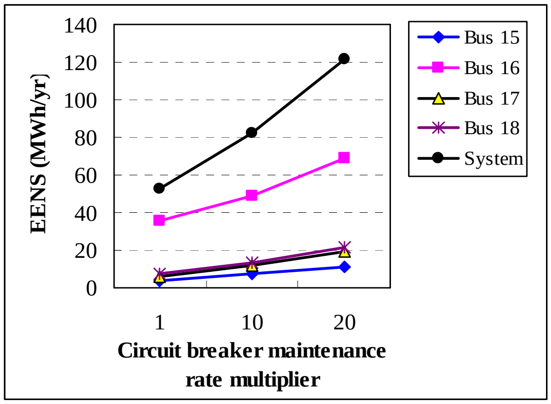

Figure 5.10: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with double bus double breaker schemes (Circuit breaker failure rates increased 10 times)

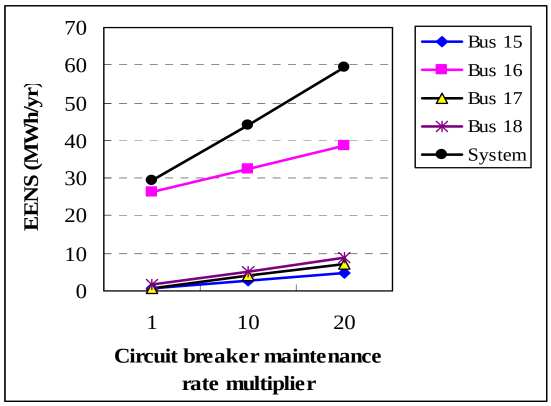

Figure 5.11: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with double bus double breaker schemes (Bus bar failure rates increased 10 times)

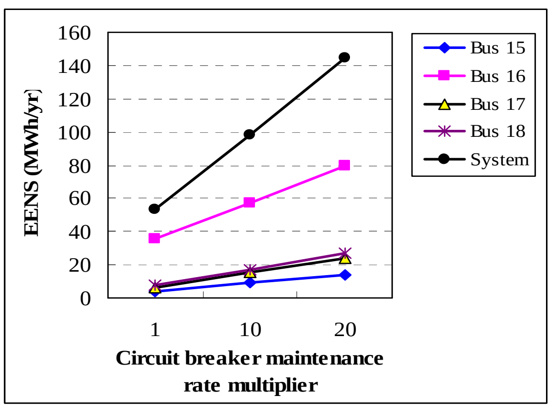

Figure 5.12: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with double bus double breaker schemes (Circuit breaker and bus bar failure rates increased 10 times)

The figures results show that the load point and system EENS increase as the circuit breaker failure rates, circuit breaker maintenance rates or bus bar failure rates increase while the impacts of their variations are different. Comparing the results, the reliability indices for the modified RBTS with double bus double breaker schemes are more sensitive to variations in circuit breaker failure rates than to variations in circuit breaker maintenance rates. The variations in bus bar failure rates have relatively small effects on the load point and system indices compared with the variations in circuit breaker failure and maintenance rates. The effects of circuit breaker maintenance rates become larger with increase in the failure rates of circuit breakers or bus bars, particularly when these failure rates increase simultaneously.

5.2.3 Sensitivity Analyses of the Modified RBTS with One and One Half Breaker Configurations

The single line diagram of the modified RBTS with one and one half breaker schemes is shown in Figure 4.13. Tables 5.5 and 5.6 show the system EENS without and with station maintenance outages as a function of the circuit breaker and bus bar failure rates respectively.

Table 5.5: System EENS without and with station maintenance outages as a function of the circuit breaker failure rates for the modified RBTS with one and one half breaker schemes

Circuit breaker failure rate multiplier	EENS (without maintenance)	EENS (including maintenance)	Increase rate (%)
1	21.50983	28.11046	30.69
10	43.80462	53.45119	22.02
20	71.79338	85.91862	19.67

Table 5.6: System EENS without and with station maintenance outages as a function of the bus bar failure rates for the modified RBTS with one and one half breaker schemes

Bus bar failure rate multiplier	EENS (without maintenance)	EENS (including maintenance)	Increase rate (%)
1	21.50983	28.11046	30.69
10	21.50983	28.7829	33.81
20	21.50983	29.13511	35.45

The effect of station maintenance outages on the system EENS becomes smaller with increase in the circuit breaker failure rates and becomes larger with increase in the bus bar failure rates. This is again because the system EENS is more sensitive to the increase in the circuit breaker failure rates than in the bus bar failure rates.

The reliability as a function of the circuit breaker failure rates, bus bar failure rates and circuit breaker maintenance rates is shown in Figures 5.13-5.18. Station maintenance outages are included in these analyses.

Reliability as a function of the circuit breaker failure rates

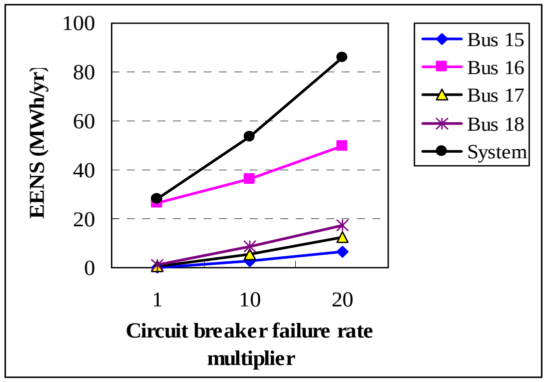

Figure 5.13: Load point and system EENS versus the circuit breaker failure rate multiplier for the modified RBTS with one and one half breaker schemes

Reliability as a function of the bus bar failure rates

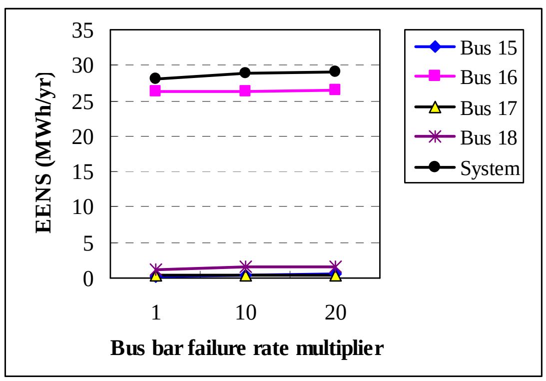

Figure 5.14: Load point and system EENS versus the bus bar failure rate multiplier for the modified RBTS with one and one half breaker schemes

Reliability as a function of the circuit breaker maintenance rates

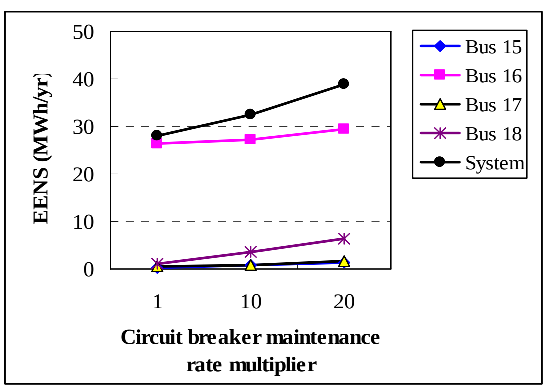

Figure 5.15: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with one and one half breaker schemes

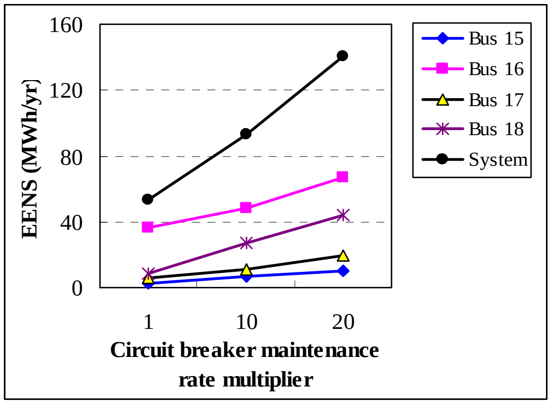

Figure 5.16: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with one and one half breaker schemes (Circuit breaker failure rates increased 10 times)

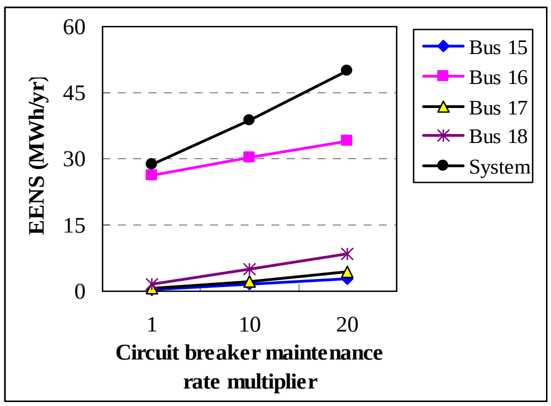

Figure 5.17: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with one and one half breaker schemes (Bus bar failure rates increased 10 times)

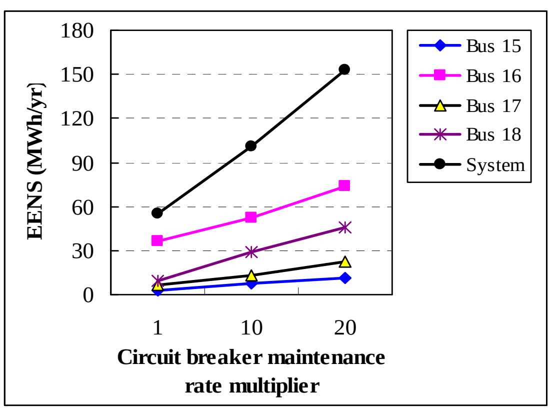

Figure 5.18: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with one and one half breaker schemes (Circuit breaker and bus bar failure rates increased 10 times)

The results of sensitivity analyses for the modified RBTS with one and one half breaker schemes are similar to those obtained for the double bus double breaker schemes. The load point and system EENS for the modified RBTS with one and one half breaker schemes, however, are more sensitive to increases in the component failure and maintenance rates.

5.2.4 Sensitivity Analyses of the Modified RBTS with One and One Third Breaker Configurations

The single line diagram of the modified RBTS with one and one third breaker schemes is shown in Figure 4.14. Tables 5.7 and 5.8 show the system EENS without and with station maintenance outages as a function of the circuit breaker and bus bar failure rates respectively. The effects of station maintenance outages on the system EENS becomes larger with increase in the circuit breaker or bus bar failure rates.

Table 5.7: System EENS without and with station maintenance outages as a function of the circuit breaker failure rates for the modified RBTS with one and one third breaker schemes

Circuit breaker failure rate multiplier	EENS (without maintenance)	EENS (including maintenance)	Increase rate (%)
1	22.17742	28.8601	30.13
10	45.99684	61.82388	34.41
20	84.7084	116.54697	37.59

Table 5.8: System EENS without and with station maintenance outages as a function of the bus bar failure rates for the modified RBTS with one and one third breaker schemes

Bus bar failure rate multiplier	EENS (without maintenance)	EENS (including maintenance)	Increase rate (%)
1	22.17742	28.8601	30.13
10	22.17742	29.21035	31.71
20	22.17742	30.12288	35.83

Reliability as a function of the circuit breaker failure rates, bus bar failure rates and circuit breaker maintenance rates are shown in Figures 5.19-5.24. Station maintenance outages are included in these analyses.

Reliability as a function of the circuit breaker failure rates

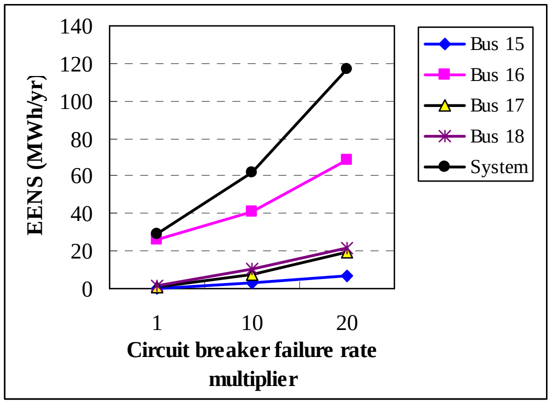

Figure 5.19: Load point and system EENS versus the circuit breaker failure rate multiplier for the modified RBTS with one and one third breaker schemes

Reliability as a function of the bus bar failure rates

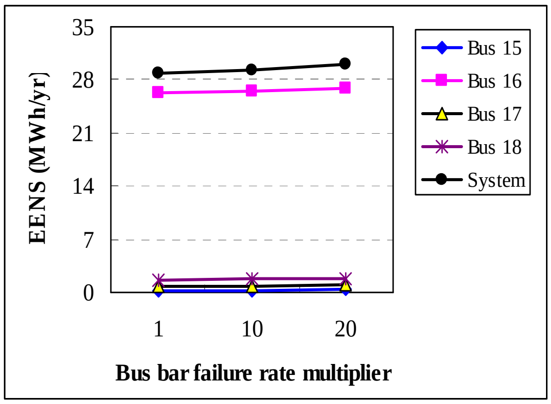

Figure 5.20: Load point and system EENS versus the bus bar failure rate multiplier for the modified RBTS with one and one third breaker schemes

Reliability as a function of the circuit breaker maintenance rates

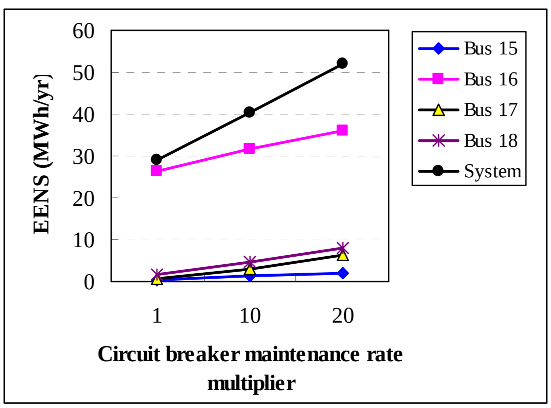

Figure 5.21: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with one and one third breaker schemes

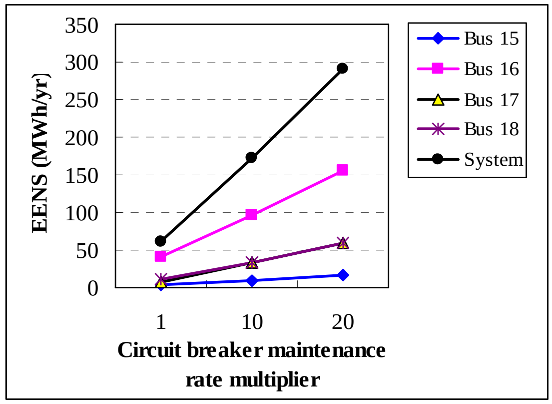

Figure 5.22: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with one and one third breaker schemes (Circuit breaker failure rates increased 10 times)

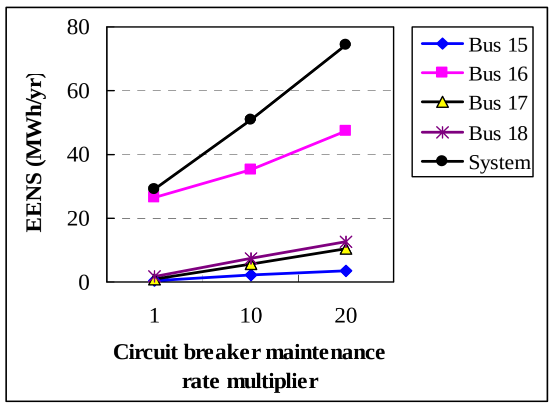

Figure 5.23: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with one and one third breaker schemes (Bus bar failure rates increased 10 times)

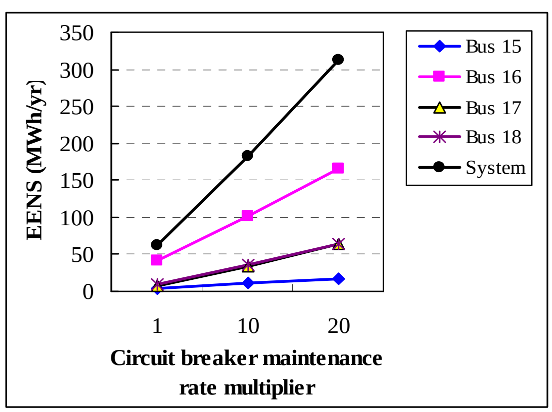

Figure 5.24: Load point and system EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with one and one third breaker schemes (Circuit breaker and bus bar failure rates increased 10 times)

The results of sensitivity analyses for the modified RBTS with one and one third breaker schemes are similar to the one with double bus double breaker schemes and one and one half breaker schemes. The load point EENS for the modified RBTS with one and one third breaker schemes, however, are more sensitive to the increases in the component failure and maintenance rates.

5.2.5 Sensitivity Comparison for the Modified RBTS with the Four Station Configurations

The effects of variations in the station component reliability parameters on the system EENS for the modified RBTS with the four different station configurations are compared in this section. Figures 5.25 and 5.26 show the increase rate in the system EENS due to including station maintenance outages, as a function of the circuit breaker and bus bar failure rates.

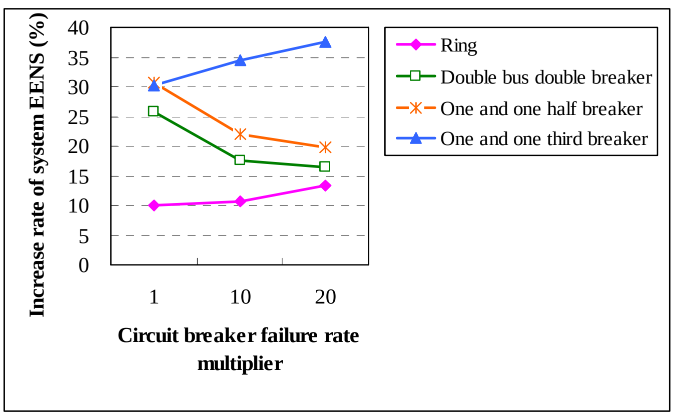

Figure 5.25: Increase rate of system EENS by including station maintenance outages as a function of the circuit breaker failure rates for the modified RBTS with the four station schemes

It can be seen in Figure 5.25 that the relative effects of station maintenance outages on the system EENS increase for the modified RBTS with ring bus schemes and with one and one third breaker schemes as the circuit breaker failure rates increase. On the other hand, the relative effects of station maintenance outages decrease for the modified RBTS with double bus double breaker schemes and with one and one half breaker schemes as the circuit breaker failure rates increase.

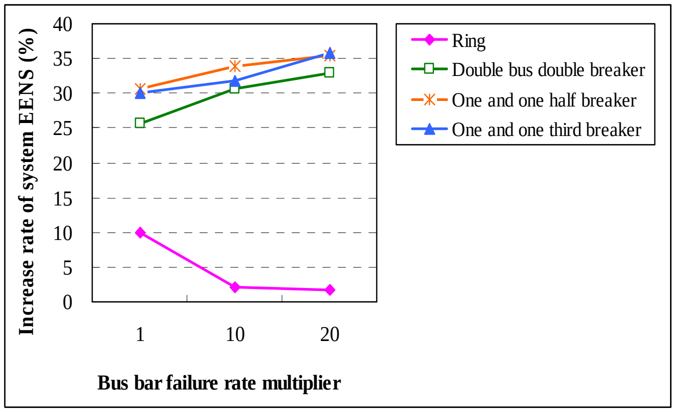

Figure 5.26: Increase rate of system EENS after including station maintenance outages as a function of the bus bar failure rates for the modified RBTS with the four station schemes

Figure 5.26 shows that the relative effects of station maintenance outages on the system EENS decrease with ring bus schemes while they increase for the other three station schemes as the bus bar failure rates increase. This is because the system EENS with ring bus schemes increase greatly as the bus bar failure rates increase.

Figures 5.27 -5.32 show the system EENS comparison with variations in the station component reliability parameters for the modified RBTS with the four station configurations. The station related maintenance outages are incorporated in all these analyses.

Reliability as a function of the circuit breaker failure rates

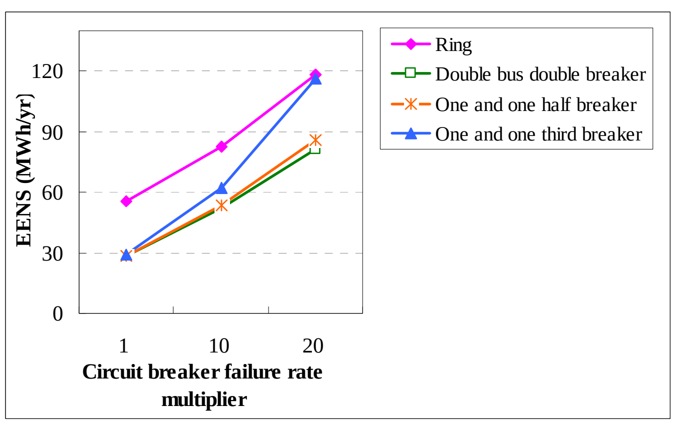

Figure 5.27: System EENS versus the circuit breaker failure rate multiplier for the modified RBTS with the four station schemes

Reliability as a function of the bus bar failure rates

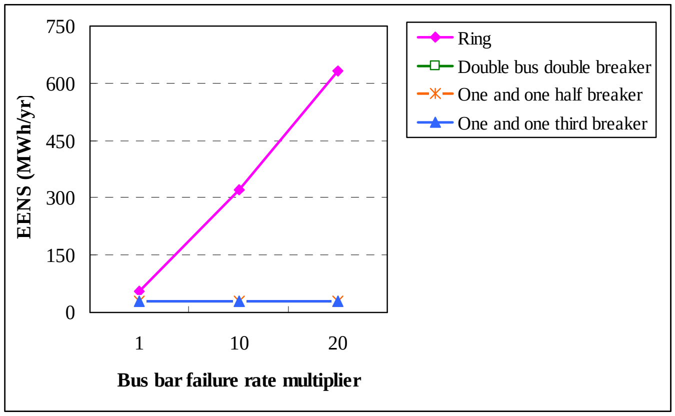

Figure 5.28: System EENS versus the bus bar failure rate multiplier for the modified RBTS with the four station schemes

Reliability as a function of the circuit breaker maintenance rates

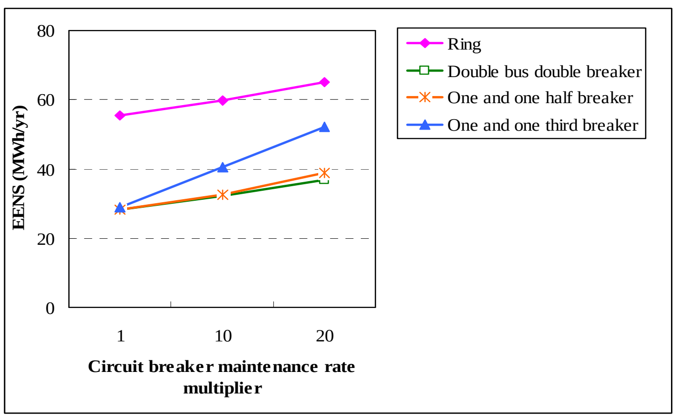

Figure 5.29: System EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with the four station schemes

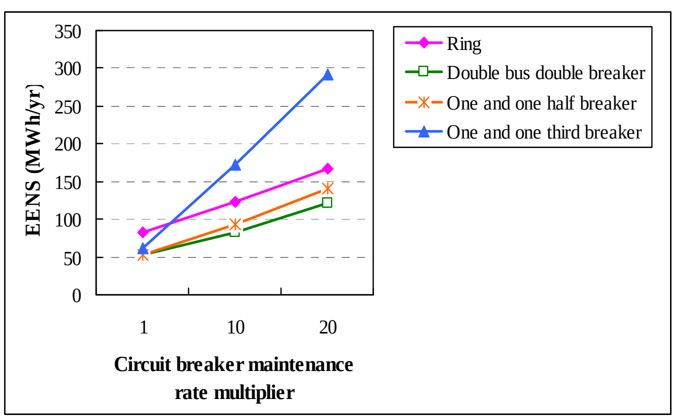

Figure 5.30: System EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with the four station schemes
(Circuit breaker failure rates increased 10 times)

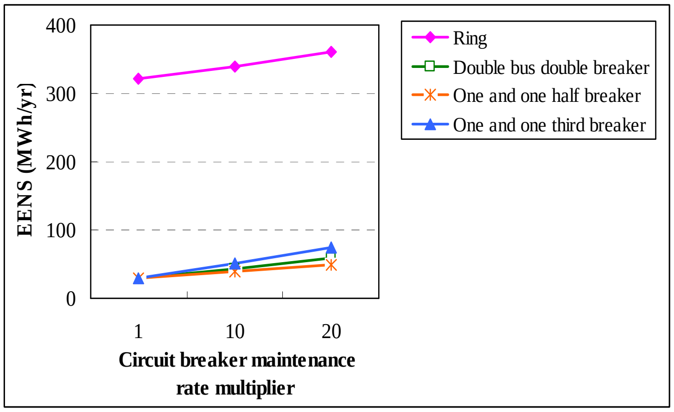

Figure 5.31: System EENS versus the circuit breaker maintenance rate multiplier for the modified RBTS with four station schemes
(Bus bar failure rates increased 10 times)

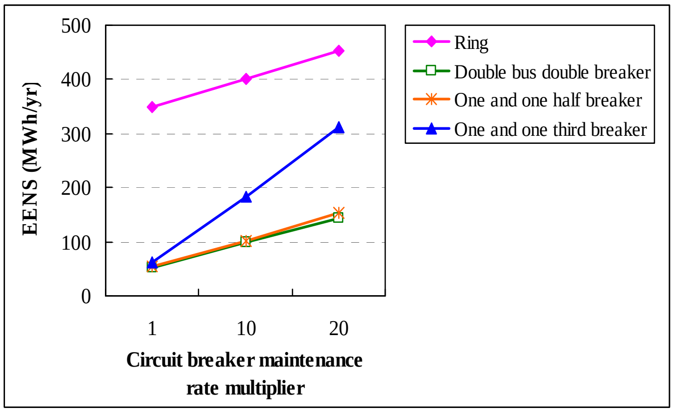

Figure 5.32: System EENS comparison versus the circuit breaker maintenance rate multiplier for the modified RBTS with four station schemes
(Circuit breaker and bus bar failure rates increased 10 times)

These results show that the modified RBTS with one and one third breaker schemes is much more sensitive to variations in the circuit breaker failure rates, compared to the system with double bus double breaker and one and one half breaker schemes. The modified RBTS with one and one half breaker schemes is relatively more sensitive to variations in circuit breaker failure rates than the system with double bus double breaker schemes. The system EENS for the modified RBTS with double bus double breaker schemes, one and one half breaker schemes, one and one third breaker schemes increase very slightly as the bus bar failure rates increase. The EENS of the modified RBTS with ring bus schemes, however, increase significantly as bus bar failure rates increase.

The variations in the circuit breaker failure rate and maintenance rate have significant effects on the reliability performance of the modified RBTS with one and one third breaker schemes. Figure 4.14 shows that system with one and one third breaker configurations has a number of extra breakers at several load points. These breakers are intended for future expansion of the system and should be added when required in the future.

Increases in the circuit breaker maintenance rates have comparatively small effects on the system indices compared with increases in the circuit breaker failure rates. The effects on the system EENS of variations in the circuit breaker maintenance rates are greater than those due to variations in the bus bar failure rates for the modified RBTS with double bus double breaker, one and one half breaker and one and one third breaker schemes. The effects of circuit breaker maintenance rates increase with increase in the circuit breaker or bus bar failure rates, particularly when both of them increase. This implies that the effects of station maintenance outages become larger as station components age.

5.3 Sensitivity Analyses of the IEEE-RTS with Two Different Station Configurations

The IEEE-RTS is a relatively large composite system and it is not necessary to examine all the load point indices as a function of the station component reliability data. Sensitivity studies are focused on the load points at the six stations selected previously. The studies in this section examine and compare the impacts of variations in the station component reliability data on the load points at Stations 3, 8, 10, 13, 15 and 18 and on the system indices. The IEEE-RTS with ring bus schemes and with mixed station schemes are shown in Figures 4.18 and 4.21 respectively. The station component reliability data on the 138kV and 230kV sides were varied separately to examine their effects on the IEEE-RTS reliability performance. Station maintenance outages are included in the analyses.

5.3.1 Reliability as a Function of the Parameters on the 138kV Side

Sensitivity analyses were concentrated on the load point EENS at Station 3, 8 and 10 for the IEEE-RTS with ring bus schemes and with mixed station schemes. The results are designated as ‘Ring’ and ‘Mixed’ respectively in the following discussion. The load point reliability performance on the 230kV side experiences minimal changes as the 138kV station component data are varied and these results are therefore not shown.

Load point reliability as a function of the 138kV circuit breaker failure rates

The load point EENS at Station 3, 8 and 10 for the IEEE-RTS with ring bus configurations and with mixed station configurations as a function of the 138kV circuit breaker failure rates are shown in Figure 5.33 and Table E.1 (Appendix E).

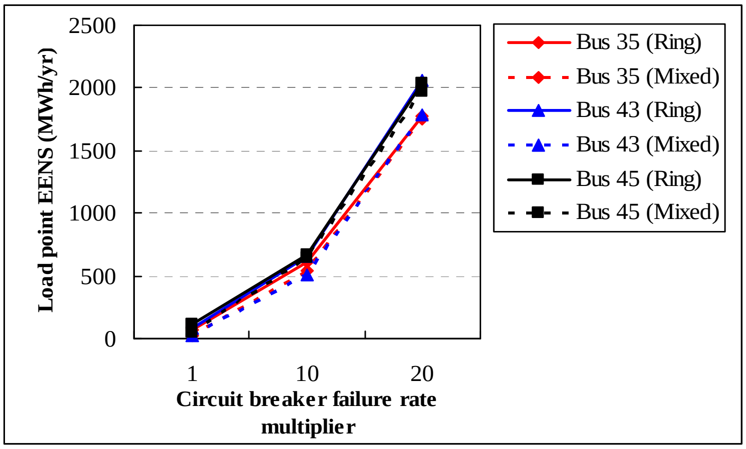

Figure 5.33: Selected load point EENS as a function of the 138kV circuit breaker failure rates

It can be seen from Figure 5.33 that the load point EENS at Buses 35, 43 and 45 (Stations 3, 8, 10) for the IEEE-RTS with ring bus schemes is always higher than those for the IEEE-RTS with mixed station schemes as the circuit breaker failure rates increase. The modification of Station 8 provides more reliability benefit in this case because there is a greater decrease in its load point EENS, compared with the load point EENS at other stations.

Load point reliability as a function of the 138kV bus bar failure rates

Figure 5.34 shows a comparison of the load point EENS at Stations 3, 8 and 10 for the IEEE-RTS with ring bus configurations and with mixed station configurations as the bus bar failure rates are varied.

An advantage of a one and one half station configuration is clearly shown in Figure 5.34. The load point EENS at Station 3, 8 and 10 for the IEEE-RTS with ring bus schemes increase significantly as the bus bar failure rates increase while those for the IEEE-RTS with mixed station schemes increase only slightly.

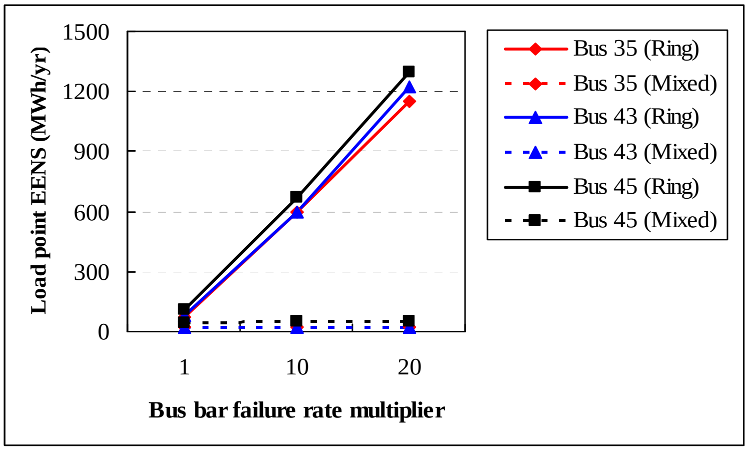

Figure 5.34: Selected load point EENS as a function of the 138kV bus bar failure rates

Load point reliability as a function of the 138kV circuit breaker maintenance rates

Figures 5.35-5.38 show comparisons of the load point EENS at Stations 3, 8 and 10 for the IEEE-RTS with ring bus configurations and with mixed station configurations as the 138kV circuit breaker maintenance rates are increased. Four different cases were studied as shown in the figures.

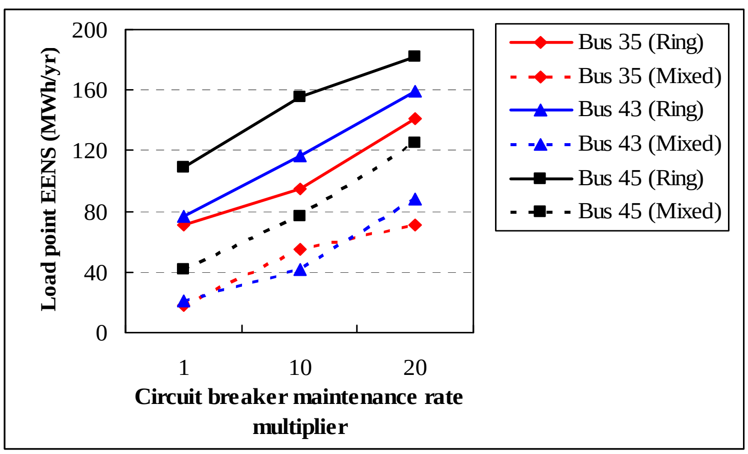

Figure 5.35: Selected load point EENS as a function of the 138kV circuit breaker maintenance rates

Figure 5.35 shows that the load point EENS at Buses 35, 43 and 45 (Stations 3, 8 and 10) for the system with mixed station schemes are lower than those for the system with ring bus schemes though they all increase as the breaker maintenance rates increase. The selected load point reliabilities improve after the station configurations are modified.

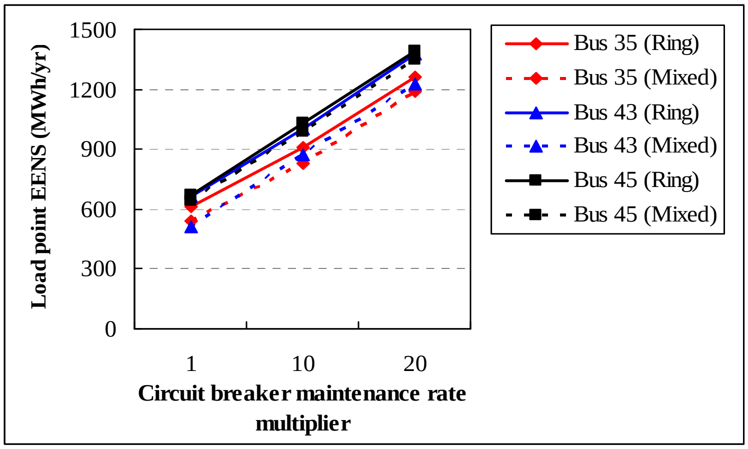

Figure 5.36: Selected load point EENS as a function of the 138kV circuit breaker maintenance rates (Circuit breaker failure rate increased 10 times)

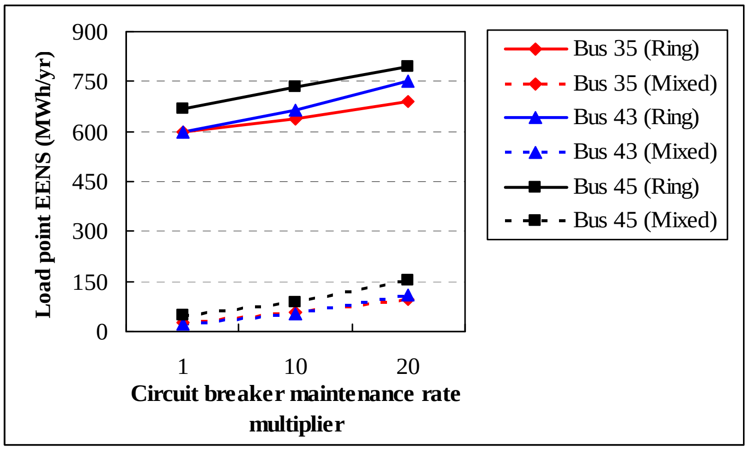

Figure 5.37: Selected load point EENS as a function of the 138kV circuit breaker maintenance rates (Bus bar failure rate increased 10 times)

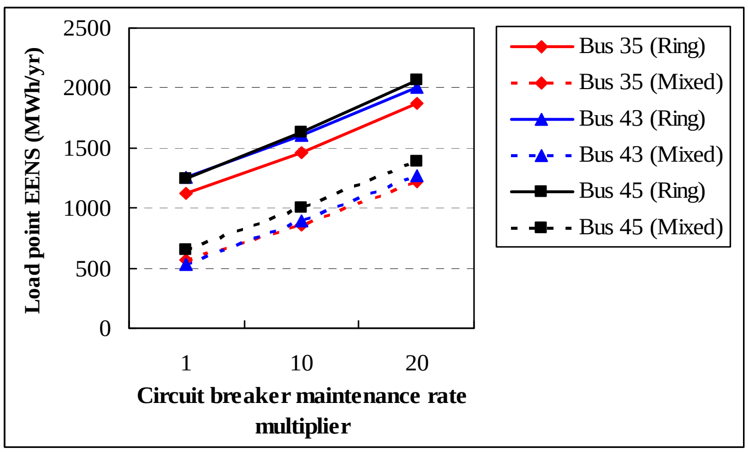

Figure 5.38: Selected load point EENS as a function of the 138kV circuit breaker maintenance rates (Circuit breaker and bus bar failure rates increased 10 times)

It can also be seen from Figures 5.36 to 5.38 that the load point EENS decrease significantly after the three ring bus stations are modified to one and one half breaker configurations. The modification of Station 8 provides more benefit as there is a greater decrease in its load point EENS.

The results show that the load point EENS on the 138kV side of the IEEE-RTS with ring bus schemes and with mixed station schemes increase as the circuit breaker failure rates, circuit breaker maintenance rates and bus bar failure rates increase. The impacts of these variations are however, quite different. Circuit breaker maintenance rates have relatively small effects on the system indices compared with circuit breaker failure rates. The effects of circuit breaker maintenance rates become larger with increase in the failure rates of circuit breakers, or bus bars or both. This implies that the effects of station maintenance outages become larger as station components age. The load point EENS are more sensitive to variations in the circuit breaker maintenance rate when circuit breaker failure rates increase, compared with the case when bus bar failure rates increase.

5.3.2 Reliability as a Function of the Parameters on the 230kV Side

Sensitivity analyses in this subsection are focused on the load points at Stations 13, 15 and 18 in the IEEE-RTS with ring bus schemes and with mixed station schemes.

Load point reliability as a function of the 230kV circuit breaker failure rates

The load point EENS at Buses 49, 51 and 61 (Stations 13, 15 and 18) for the IEEE-RTS with ring bus configurations and with mixed station configurations as a function of the 230kV circuit breaker failure rates are shown in Table 5.9 and Figure 5.39.

It can be seen from Tables 5.9 and Figure 5.39 that the load point EENS at buses 51 and 61 (Stations 15, 18) for the IEEE-RTS with ring bus schemes is always higher than those for the IEEE-RTS with mixed station schemes as the circuit breaker failure rates increase. The load point EENS at bus 49 (Station 13) for the IEEE-RTS with ring bus schemes, however, becomes smaller than that for the system with mixed station schemes as the circuit breaker failure rates increase. This is due to the particular topology of this station, and is discussed further in Section 5.3.4. The modification of Station 15 provides more reliability benefit in this case because there is a greater decrease at its load point

EENS, compared with the load point EENS at the other stations. Station 15 has the most equipment in the IEEE-RTS and requires a more reliable configuration.

Table 5.9: Selected load point EENS as a function of the 230kV circuit breaker failure rates

Circuit breaker failure rate multiplier	1	10	20
Bus 49 (Ring)	124.765	1098.829	3198.813
Bus 49 (Mixed)	44.584	1075.068	3237.062
Bus 51 (Ring)	639.453	2540.159	7281.763
Bus 51 (Mixed)	568.037	1793.393	4311.035
Bus 61 (Ring)	145.437	1296.169	3944.767
Bus 61 (Mixed)	93.348	1176.547	3837.062

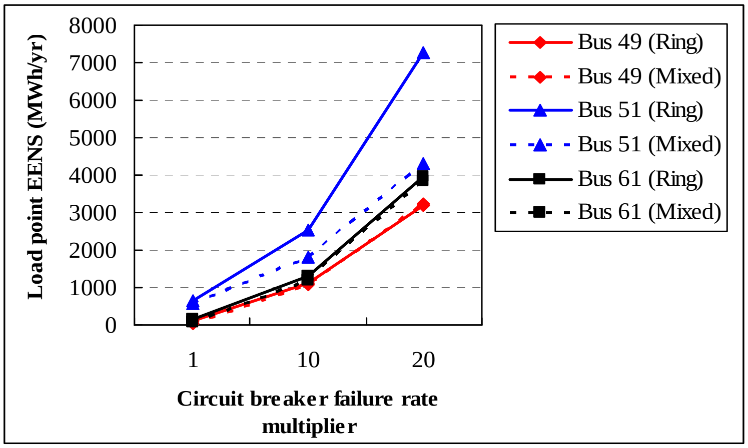

Figure 5.39: Selected load point EENS as a function of the 230kV circuit breaker failure rates

Load point reliability as a function of the 230kV bus bar failure rates

Figure 5.40 shows a comparison of the load point EENS at Stations 13, 15 and 18 for the IEEE-RTS with ring bus configurations and with mixed station configurations as the 230kV bus bar failure rates are varied. It can be seen that the load point EENS increase after station maintenance outages are incorporated. The advantage of a one and one half station configuration is shown in this figure. The load point EENS at buses 49, 51 and 61 for the IEEE-RTS with ring bus schemes increase rapidly as the bus bar failure rates increase while those for the IEEE-RTS with mixed station schemes increase very slightly.

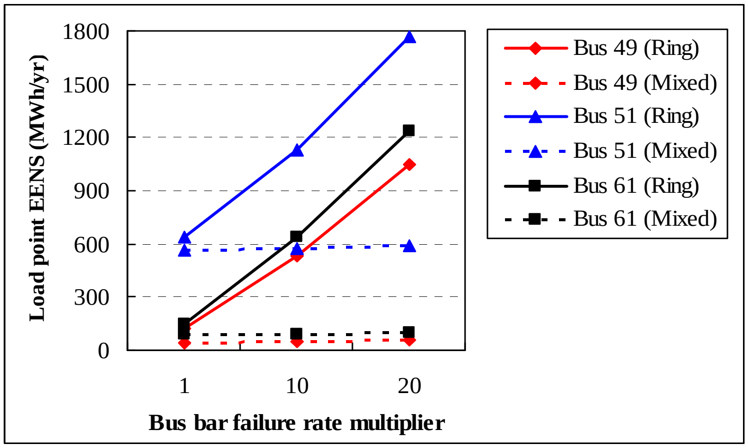

Figure 5.40: Selected load point EENS as a function of the 230kV bus bar failure rates

Load point reliability as a function of the 230kV circuit breaker maintenance rates

Figures 5.41 to 5.44 show comparisons of the load point EENS at Station 13, 15 and 18 for the IEEE-RTS with ring bus configurations and with mixed station configurations as the 230kV circuit breaker maintenance rates are varied.

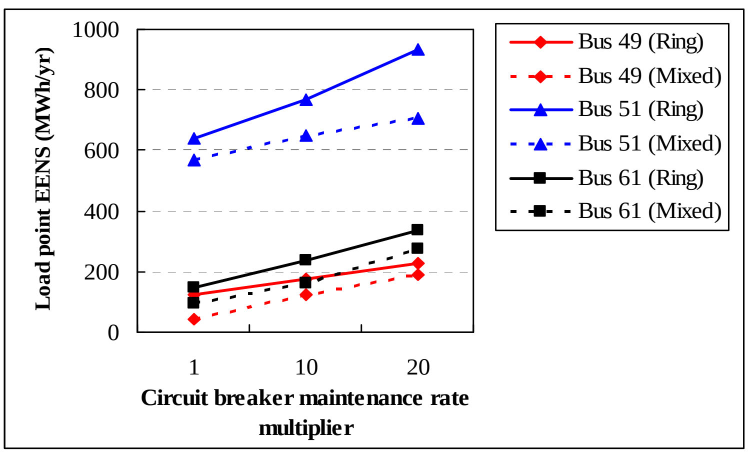

Figure 5.41: Selected load point EENS as a function of the 230kV circuit breaker maintenance rates

Figure 5.41 shows that the load point EENS at Buses 49, 51 and 61 for the IEEE-RTS with ring bus schemes are relatively higher than those with mixed station schemes though they all increase as the breaker maintenance rates increase. The load point reliabilities improve after the station configurations are modified.

It can be seen from Figures 5.43 to 5.44 that the load point EENS decrease significantly after the station ring bus configurations are modified to one and one half breaker configurations. The modification of Station 15 provides the most benefit.

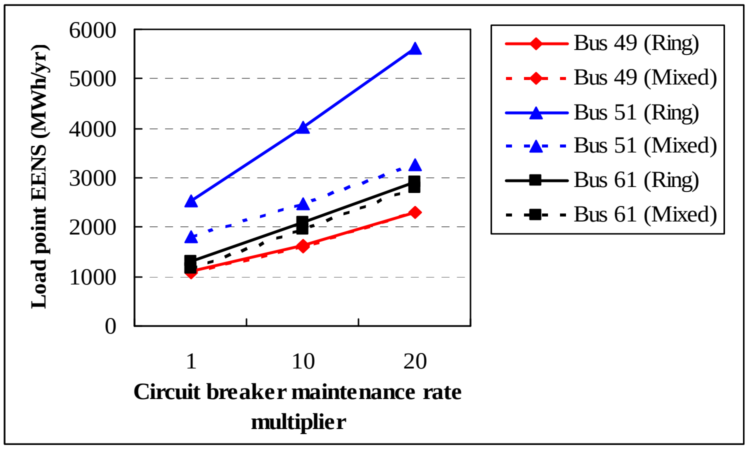

Figure 5.42: Selected load point EENS as a function of the 230kV circuit breaker maintenance rates (Circuit breaker failure rate increased 10 times)

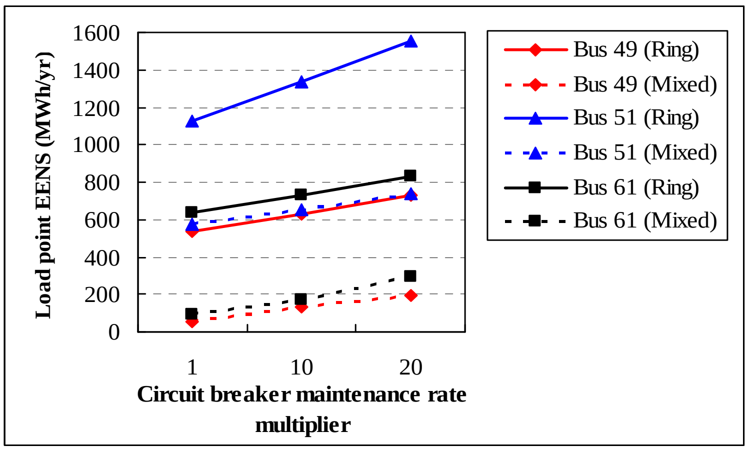

Figure 5.43: Selected load point EENS as a function of the 230kV circuit breaker maintenance rates (Bus bar failure rate increased 10 times)

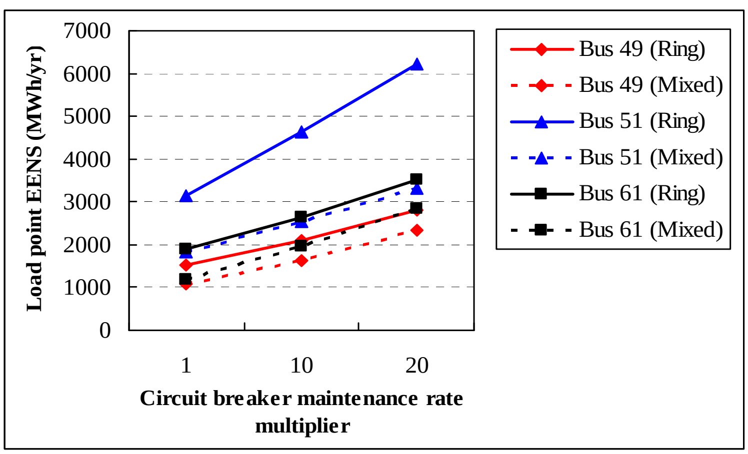

Figure 5.44: Selected load point EENS as a function of the 230kV circuit breaker maintenance rates (Circuit breaker and bus bar failure rates increased 10 times)

The results show that the selected load point EENS of the IEEE-RTS with ring bus schemes and with mixed station schemes increase as the 230kV circuit breaker failure rates, circuit breaker maintenance rates and bus bar failure rates increase. The impacts of the variations on the load point reliability, however, are quite different. Circuit breaker maintenance rates have a relatively small effect on the load point indices compared with circuit breaker failure rates. The effects of circuit breaker maintenance rates, however, become larger with increase in the failure rates of circuit breakers, or bus bars or both. The load point EENS are more sensitive to variations in the circuit breaker maintenance rates when the circuit breaker failure rates increase, compared with when the bus bar failure rates increase. This indicates that the effects of station maintenance outages become larger when station components age.

5.3.3 System Reliability Comparison

Station component reliability data on the 138kV side and 230kV side were varied to examine their effects on the overall system reliability performance of the IEEE-RTS. Four cases were studied and are shown in Figure 5.45-5.50.

System reliability as a function of circuit breaker failure rates

Figure 5.45 shows a comparison of the system EENS for the IEEE-RTS with ring bus configurations and with mixed ring bus and one and one half breaker configurations as a function of the 138kV and 230kV circuit breaker failure rates.

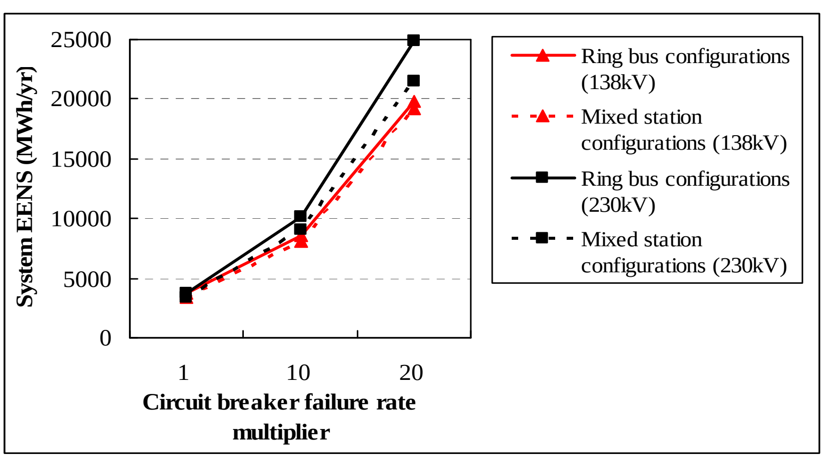

Figure 5.45: System EENS comparison as a function of the circuit breaker failure rate

It can be seen that the system EENS for the IEEE-RTS with mixed station schemes is relatively lower than for the IEEE-RTS with ring bus schemes when the circuit breaker failure rates increase. Station modifications on the 230kV side provide more benefit than those on the 138kV side as the system EENS with ring bus schemes decrease considerably after the modifications. One reason for this is because the modified stations on the 230kV side carry heavier loads than those on the 138kV side.

Figure 5.45 also shows that the system EENS for the IEEE-RTS with ring bus schemes and with mixed station schemes is more sensitive to the variations in the 230kV circuit breaker failure rates than to the 138kV circuit breaker failure rates. One obvious reason is because the 230kV circuit breaker failure rates are larger than the 138kV values. This suggests that the effects of the 230kV circuit breakers on the overall system reliability performance will exceed those of the 138kV breakers as the circuit breakers age. This is valuable information in the system design and reinforcement process and could lead to using higher quality circuit breakers in the high voltage side of the system.

System reliability as a function of bus bar failure rates

Figure 5.46 shows a comparison of the system EENS for the IEEE-RTS with ring bus configurations and with mixed station configurations as a function of the 138kV and 230kV bus bar failure rates.

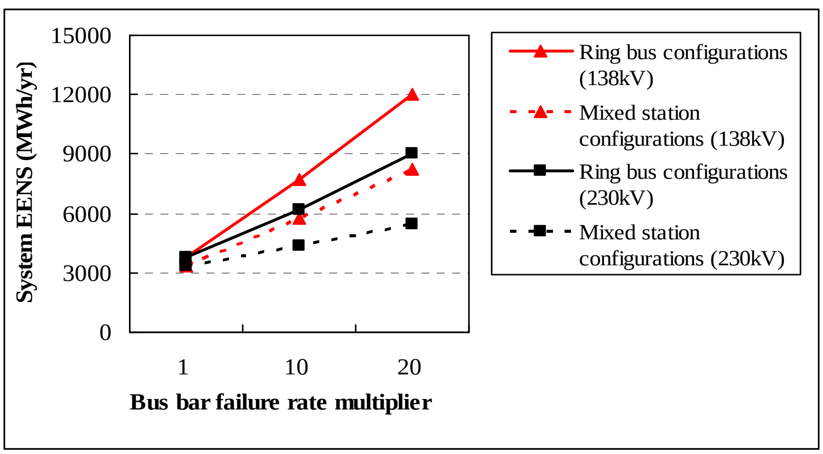

Figure 5.46: System EENS comparison as a function of the bus bar failure rate

It can be seen that the system reliability for the IEEE-RTS with mixed station schemes is significantly better than that for the system with ring bus schemes as the bus bar failure rates increase. The results also show that the system EENS for the IEEE-RTS with ring bus schemes and with mixed station schemes is more sensitive to the variations in the 138kV bus bar failure rates than to the 230kV bus bar failure rates. The effects of the 138kV bus bars on the overall system reliability performance exceed those of the 230kV bus bars as the bus bars age.

System reliability as a function of circuit breaker maintenance rates

Figures 5.47 to 5.50 show comparisons of system EENS for the IEEE-RTS with ring bus configurations and with mixed station configurations as a function of the 138kV and 230kV circuit breaker maintenance rates for four cases.

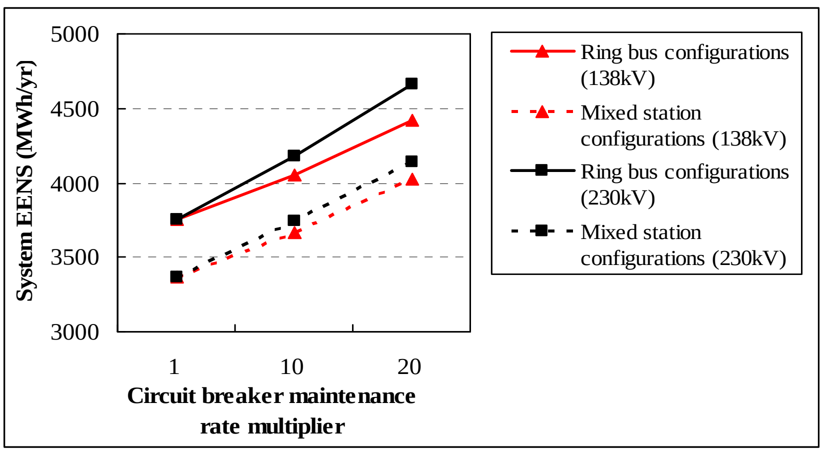

Figure 5.47: System EENS comparison as a function of the circuit breaker maintenance rates

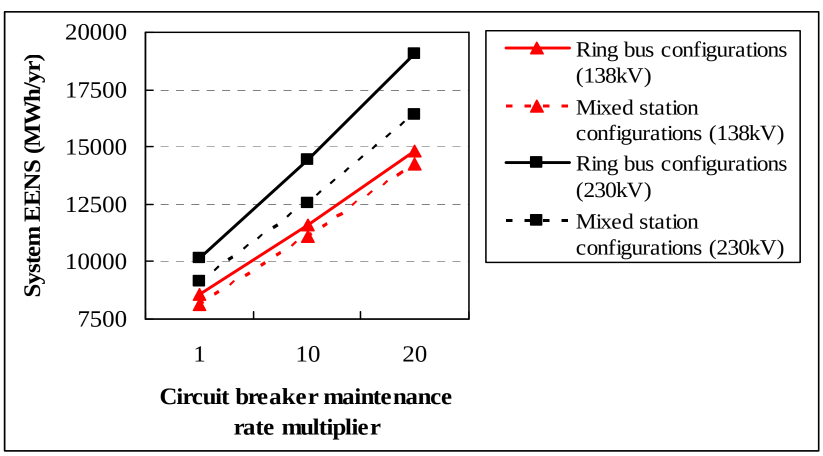

Figure 5.48: System EENS comparison as a function of the circuit breaker maintenance rates (Circuit breaker failure rates increased 10 times)

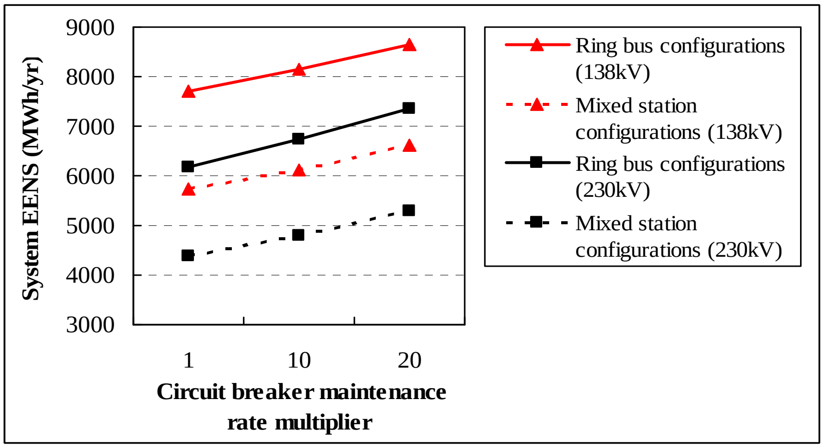

Figure 5.49: System EENS comparison as a function of the circuit breaker maintenance rate (Bus bar failure rates increased 10 times)

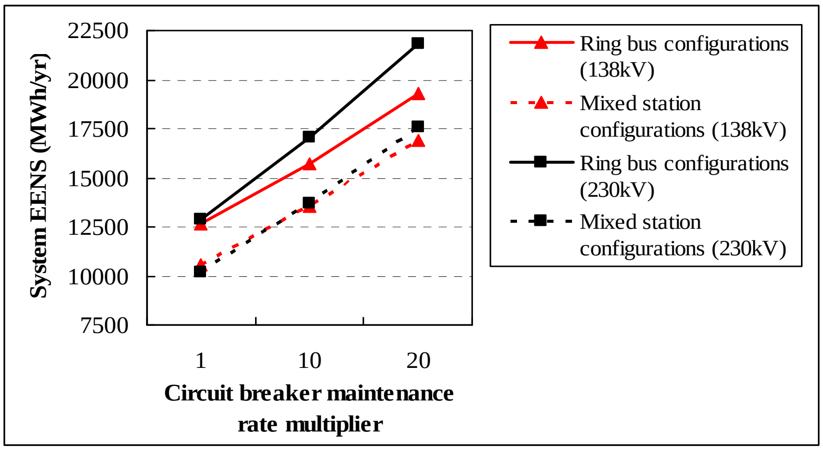

Figure 5.50: System EENS comparison as a function of the circuit breaker maintenance rate (Circuit breaker and bus bar failure rates increased 10 times)

It can be seen from Figure 5.47 that system EENS decrease considerably after modifying the station configurations. It also shows that the system EENS for the IEEE-RTS with ring bus schemes and with mixed station schemes is more sensitive to variations in the 230kV circuit breaker maintenance rates than to the 138kV circuit breaker maintenance rates. This implies that the effects of the 230kV circuit breaker maintenance rates on the overall system reliability performance are greater than the 138kV values. It is therefore better to reduce the number of maintenance actions on the 230kV side of this system during the useful life of the station components.

Figure 5.48 shows a system EENS comparison as a function of the circuit breaker maintenance rate as circuit breaker failure rates increased by a factor of 10. It can be seen from the figure that the system EENS for the IEEE-RTS with mixed station schemes is lower than that for the IEEE-RTS with ring bus schemes as the circuit breaker maintenance rates increase. The station modifications on the 230kV side provide more benefit than on the 138kV side. The effects of the 230kV circuit breaker maintenance rates on the overall system reliability performance are greater than the 138kV values as the circuit breakers deteriorate.

The system EENS comparison as a function of the circuit breaker maintenance rate when the bus bar failure rates increased by a factor of 10 is shown in Figure 5.49. It can be seen from the figure that the system EENS of the IEEE-RTS with ring bus schemes is much higher than that of the IEEE-RTS with mixed station schemes in this case. The effects of circuit breaker maintenance rates on the 138kV side are very similar to those on the 230kV side as bus bars age.

Figure 5.50 shows a system EENS comparison as a function of the circuit breaker maintenance rate as both the circuit breaker and bus bar failure rates increase 10 times. It can be seen from the figure that the system EENS for the IEEE-RTS with mixed station schemes is lower than for the IEEE-RTS with ring bus schemes in this case. The effects of circuit breaker maintenance rates on the 230kV side are greater than those on the 138kV side as all the station components age.

Figures 5.47-5.50 show that the station modifications on the 230kV side provide more benefit than those on the 138kV side. The system EENS for the IEEE-RTS are in general considerably lower due to the modifications, but the modified stations on the 230kV side have heavier loads than those on the 138kV side.

5.3.4 Sensitivity Analyses for Generating Station 13 of the IEEE-RTS

Sensitivity studies were performed on the 138kV side and 230kV side of the IEEE-RTS with ring bus schemes and with mixed station schemes in the previous studies. The load point and system EENS as a function of the 230kV circuit breaker failure rates for the IEEE-RTS with ring bus schemes and with mixed station schemes are shown in Tables E.2 and E.3 (Appendix E) respectively. The results show that the load point EENS at Station 13 for the IEEE-RTS with ring bus schemes is lower than that for the IEEE-RTS with mixed ring bus and breaker and a half schemes when the 230kV circuit breaker failure rates increase by a factor of 20. The sensitivity studies in this section focus on the effects of alternative terminal connections at generation station 13.

The circuit breaker failure rates were increased only at Station 13 in the following analyses in order to examine the effects. The load point and system EENS as a function of the 230kV circuit breaker failure rates at Station 13 for the IEEE-RTS with ring bus schemes and with mixed station schemes respectively are shown in Tables E.4 and E.5. The results show that the load point EENS at Station 13 for the IEEE-RTS with ring bus schemes is lower than that for the IEEE-RTS with mixed station schemes while the overall system EENS is higher than that for the IEEE-RTS with mixed station schemes. It can be seen from Table E.4 that for the IEEE-RTS with ring bus schemes, the load point EENS at Stations 9, 13, 15, 19 increases as the circuit breaker failure rates in Station 13 increase. This is different from Table E.5 for the IEEE-RTS with mixed station schemes, in which the variations in circuit breaker failure rates at Station 13 mainly affect the load point EENS of Station 13.

As noted earlier, generation system failures are the major contributors to the IEEE-RTS reliability indices. In the IEEE-RTS with ring bus configurations shown in Figure 4.21, the load point at Station 13 can be supplied by transmission line 20 or 22, or by generators in Station 13. Generator failures are not the only factors that cause failures of this load point. Table E.4 also shows that failure events in Station 13 also affect the load point indices at other stations.

Sensitivity analyses of Station 13 shows that station terminal connection topologies can have considerable effects on the load point and system reliability of a composite system. Station 13 was modified to examine the effects of alternative station schemes on the load point and system reliability performance.

Modified configuration I for Station 13

Figure 5.51 shows the modified ring bus configuration for Station 13. This modification involves interchanging G12 and Line 22. The configurations of other stations are identical as those shown in Figure 4.19.

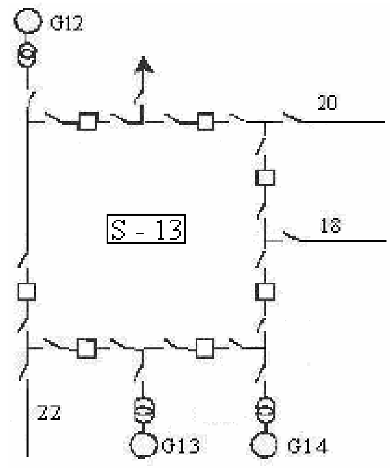

Figure 5.51: Modified ring bus configuration I for station 13

The load point and system EENS as a function of the 230kV circuit breaker failure rates at Station 13 for modification I are shown in Table E.6. This table shows that the load point EENS at Station 13 is the major contribution to the increase in system EENS as the circuit breaker failure rates at Station 13 increase. The load point EENS at other stations increase very slightly as the circuit breaker failure rates at Station 13 increase.

The load point and system EENS as a function of the 230kV circuit breaker failure rates for modification I are shown in Table E.7. Comparing Tables E.6 with E.5 and Tables E.7 with E.3, the load point EENS at Station 13 and system EENS for the IEEE-RTS with modification I is higher than those for the system with mixed station configurations.

Modified configuration II for Station 13

Figure 5.52 shows modified configuration II for Station 13. The modified configuration I was extended by also interchanging G14 and Line 20. The configurations of the other stations are identical to those shown in Figure 4.21. The load point and system EENS as a function of the 230kV circuit breaker failure rates for the IEEE-RTS with modified ring bus configuration II are shown in Table E.8.

Comparing Table E.8 with Table E.7, the load point EENS at Station 13 and the system EENS for the IEEE-RTS with modified ring bus configurations II are higher than those for the system with modification I, and much higher than those for the system with the original ring bus configurations.

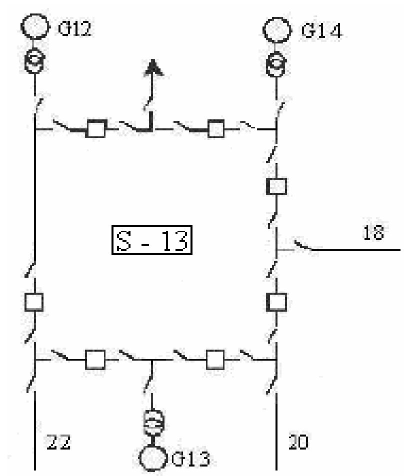

Figure 5.52: Modified ring bus configuration II for station 13

Sensitivity analyses of the IEEE-RTS with four different station schemes

The load point EENS at Station 13 and the system EENS versus the 230kV circuit breaker failure rates for the IEEE-RTS with four different station schemes are shown in Figures 5.53 and 5.54.

Comparing Figures 5.53 and 5.54, the IEEE-RTS with mixed ring bus and one and one half breaker configurations is the most reliable system and the IEEE-RTS with modified ring bus configuration II is the least reliable system. The load point and system EENS for the IEEE-RTS with modified ring bus configuration I are higher than that for the IEEE-RTS with the original ring bus configurations as the circuit breaker failure rates increase. The IEEE-RTS with the original ring bus configurations is relatively more reliable than with modification I and with modification II.

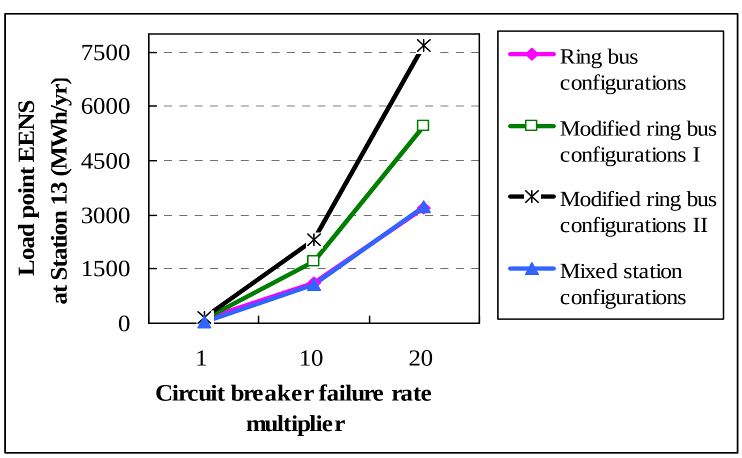

Figure 5.53: Load point EENS at Station 13 versus the 230kV circuit breaker failure rates for the IEEE-RTS with four different station schemes

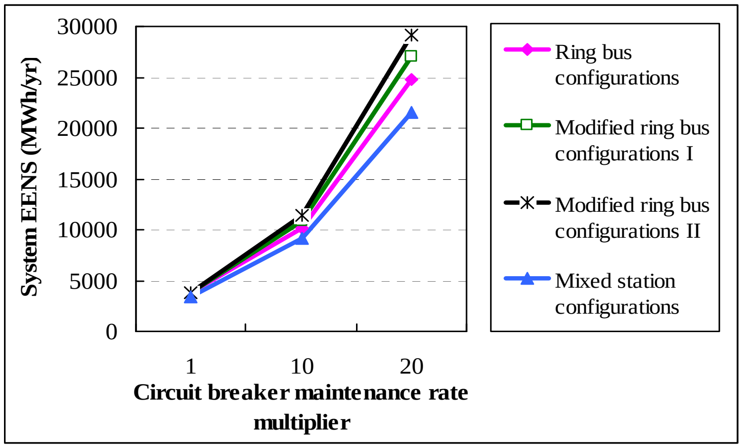

Figure 5.54: System EENS versus the 230kV circuit breaker failure rates for the IEEE-RTS with four different station schemes

The effects of station topologies on the load point and system reliability indices are investigated by modifying ring bus station 13 using two alternative configurations. The comparison of the sensitivity analyses for the IEEE-RTS with the four different station schemes shows that station configurations and topologies can have considerable effect on the load point and system reliability of a composite system. The studies also show that failure events within a generating station may affect the load point indices at other stations. The analyses illustrate the importance of system probabilistic reliability analysis during the power system planning, design and reinforcement process.

5.4 Summary

The effects of variations in station component reliability parameters on the load point and system reliability of the modified RBTS and IEEE-RTS were analyzed using the minimal cut set method and the MECORE program. Four different station configurations are incorporated in the reliability sensitivity analyses of the modified RBTS. These are ring bus, double bus double breaker, one and one half breaker and one and one third breaker schemes. The analyses performed on the IEEE-RTS are done with ring bus schemes and mixed station schemes.

Sensitivity analyses were performed on the modified RBTS with the four different station configurations by varying the station component parameters. The results show that the load point and system EENS increase as the circuit breaker failure rates, circuit breaker maintenance rates and bus bar failure rates increase, while the impacts of their variations are different. Comparing the results, the reliability indices for the modified RBTS with ring bus schemes are more sensitive to variations in the bus bar failure rates than to variations in the circuit breaker failure rates. The reliability indices for the modified RBTS with double bus double breaker, one and one half breaker and one and one third breaker schemes are more sensitive to variations in the circuit breaker failure rates than to variations in the circuit breaker maintenance rates and bus bar failure rates. The modified RBTS with one and one half breaker schemes is relatively more sensitive to variations in circuit breaker failure rates than with double bus double breaker schemes. Station configurations play an important role on the load point and system reliability performance of a composite system.

The variations in the circuit breaker failure and maintenance rates have significant effects on the reliability performance of the modified RBTS with one and one third breaker schemes. The system with one and one third breaker configurations has a number of extra breakers at several load points. These breakers are intended for future expansion of the system and therefore should be added when required in the future.

The IEEE-RTS is a relatively large composite system and the sensitivity studies are comparatively complex. Sensitivity studies on this system examine and compare the impacts of variations in the station component reliability data on the load points at Stations 3, 8, 10, 13, 15 and 18 and the system indices for the IEEE-RTS with the two different station schemes. The selected load point and the entire system reliability improve after the six stations are modified to one and one half breaker configurations.

Station component reliability data on the 138kV side and 230kV side are varied separately to examine their effects on the load point and system reliability of the IEEE-RTS with the two different station schemes. The results show that the effects of the 230kV circuit breaker failure rates on the reliability performance of the IEEE-RTS with two different station schemes will exceed those of the 138kV breakers as circuit breakers age. The impacts of the 138kV bus bar failure rates on the IEEE-RTS reliability performance exceed those of the 230kV bus bars as bus bars deteriorate. The effects of circuit breaker maintenance rates on the 230kV side are greater than those on the 138kV side as all the station components age. This information could lead to using higher quality circuit breakers on the high voltage side of the system, and reducing the number of maintenance actions on the 230kV side of the system during the useful life of the station components.

Sensitivity analyses conducted on the IEEE-RTS with ring bus schemes and with mixed station schemes show that station configurations and topologies can have considerable impacts on the composite system reliability performance. Sensitivity studies on Station 13 also show that failure events within a generating station may affect the load point indices at other stations. The effects of station topologies on composite system reliability indices are illustrated by changing ring bus Station 13 to two different ring bus configurations. The sensitivity comparisons for the IEEE-RTS with the four different station schemes show that a proper station design is crucial to obtain optimal reliability performance of a composite power system.

Sensitivity analyses on the two composite systems show that circuit breaker maintenance rates have relatively small effects on the system indices compared with circuit breaker failure rates. The effects of circuit breaker maintenance rates become larger with increase in the failure rates of circuit breakers or bus bars, particularly when both the circuit breaker and bus bar failure rates increase simultaneously. This implies that the effects of circuit breaker maintenance rates become larger as station components age. The load point and system reliability degrade as station components age and they will further degrade as breaker maintenance frequencies increase. Maintenance is required to maintain electric equipment in a good operating condition and prolong its useful life. This slows down the aging process and keeps the failure rate from increasing. Maintenance during the component deterioration process provides reliability improvement because the effects of the circuit breaker failure rates on the system reliability are much larger than those of the maintenance rate. This knowledge can provide valuable information in decision-making in station design, reinforcement and maintenance planning.

The objective of performing the sensitivity studies shown in this chapter is to develop an appreciation of the changes in the system reliability as the component failure rates increase. These analyses are based on constant repair rates. During the aging or deterioration process, the failure rates increase. A component is assumed to require replacement if it fails due to aging as it can not be further repaired. Techniques to incorporate station component aging failures are described and applied to the two composite test systems in the next chapter.

Chapter 6

Incorporating Station Component Aging Failures in Composite System Reliability Evaluation

6.1 Introduction

Power system component failure can generally be divided into two categories: random failures and those arising as a consequence of deterioration (aging) [29]. The previous studies are focused on the influence of random failures of station components on composite system reliability. As noted earlier, the reliability of a composite system is a function of the individual station component reliabilities and the station configurations. Component reliability is related to the failure, repair, maintenance outage and maintenance duration rates. Component failure rates are affected by a variety of factors, such as preventive maintenance practices, designed useful life and variations in the environment. The reliability failure characteristic of electric equipment generally follows the well-known bathtub curve shown in Figure 6.1. Region I is known as the de-bugging or infant mortality period, which is not considered in this research. During Region II which is known as the component useful life, the failure rate is constant and the failure density function follows an exponential distribution. When the component reaches Region III which is designated as the wear-out period, the component failure rate increases gradually. The component reliability degrades after it reaches the onset of deterioration. Reliability analyses in Chapter 5 show that the composite system reliability degrades with increase in the station component failure rates.

The failure events of a component can be grouped into the two categories of repairable and nonrepairable. If a component fails during its useful life in which failures are assumed to occur randomly and the failure rate is constant, it can be restored to

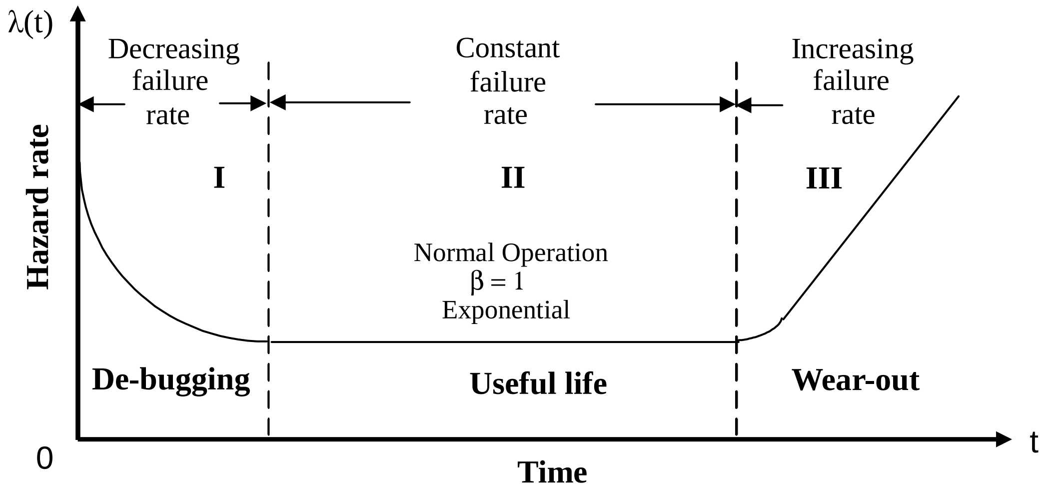

Figure 6.1: Component hazard rate as a function of age

service after being repaired. When the component reaches the deterioration point, its failure rate increases and failures due to aging are also possible. Sensitivity analyses are presented in Chapter 5 to illustrate the effects on the load point and system reliability of the two composite systems of increases in the station component failure rates. The analyses were based on the assumption that a component can be restored to service after being repaired. Component aging failure events, however, are considered to be nonrepairable and alternative approaches are required.

Aging failures of station components, such as transformers, circuit breakers and bus bars, are a major concern in composite system planning and operation as more and more station components approach the wear-out phase. This chapter presents two different evaluation techniques to incorporate station component aging failures in composite system reliability evaluation. In the first technique, a component cannot be restored to service once it fails due to aging. As a result, there is no concept of the repair time associated with the failure. In the second technique a component is replaced when it fails due to aging. Station components such as circuit breakers or bus bars are comparatively easy to replace and the component outage time is the replacement time. Approximate evaluation approaches are developed to incorporate aging failures of station components, such as circuit breakers and bus bars in composite system reliability evaluation. The first technique is used to incorporate transformer aging failures in the reliability assessment of the modified RBTS and the IEEE-RTS. The second technique is applied to include circuit breaker and bus bar aging failures in a modified RBTS reliability evaluation.

6.2 Two Evaluation Methods to Incorporate Component Aging Failures

Two different methods are presented in this section and used to evaluate station component reliability parameters including aging failures. In the first technique, two probability distributions, the normal distribution and the Weibull distribution, are used to calculate the component unavailability due to aging failures. In the second technique, additional mathematical models are proposed to consider station component aging failures. Approximate methods are also developed to incorporate aging failures in the reliability evaluation of circuit breakers and bus bars.

6.2.1 Method I

Evaluation method I is based on the concepts in [39-41]. A major point in this method is that a component effectively disappears when it fails due to aging since aging failures are nonrepairable events. The component aging failures process can be modeled by either a normal distribution or a Weibull distribution. This is different from the useful life failure model which uses the exponential distribution and constant failure and repair rates. The calculation of the component unavailability is described in the following using a transformer as an example.

Calculation approach for component unavailability due to aging failures

The probability of occurrence of an aging failure is defined as the conditional probability that an aging failure of a component will take place within a specified period t given that it has survived for T years. This probability can be obtained as follows:

$$P_f = \frac{\int_T^{T+t} f(t)dt}{\int_T^{\infty} f(t)dt} \tag{6.1}$$

where $f(t)$ is the failure density function.

Component unavailability due to an aging failure can be defined as the probability that a component is unavailable due to an aging failure during a specified time period t given that it has survived for T years. It is the conditional mathematical expectation of the time when the component is unavailable due to an aging failure during t divided by the period considered (t) [39].

Using Equation 6.1, the aging failure probability in a small interval Δx at any point x within t can be calculated by

$$P_f = \frac{\int_T^{T+x+\Delta x} f(t)dt - \int_T^{T+x} f(t)dt}{\int_T^{\infty} f(t)dt} \tag{6.2}$$

If the component fails at the point x, the unavailable duration within t is t - x. Because x can be any point between [0, t], the average unavailability can be mathematically expressed using the following integral:

$$U_a = \frac{1}{t}\int_{x=0}^{t} \lim_{\Delta x \to 0} \frac{\int_T^{T+x+\Delta x} f(t)dt - \int_T^{T+x} f(t)dt}{(\int_T^{\infty} f(t)dt)\cdot \Delta x}(t-x)dx \tag{6.3}$$

Equation 6.3 can be expressed by the discretization method. The period t is divided into N equal intervals, each having a length Δx. It is assumed that Δx is small enough so that the failure probability at any point within Δx is approximately constant. The average unavailability duration within t is

$$UD_i = t - (2i-1)\Delta x / 2 \qquad (i = 1, 2, \ldots, \mathrm{N}) \tag{6.4}$$

where UD_i is the average unavailable duration within t when the component fails in the ith interval and Δx is the length of each interval.

The unavailability of a component in the specified subsequent period t is

$$U_a = \sum_{i=1}^{N} P_i \cdot UD_i / t \tag{6.5}$$

where

$$P_i = \frac{\int_T^{T+i\Delta x} f(t)dt - \int_T^{T+(i-1)\Delta x} f(t)dt}{\int_T^{\infty} f(t)dt} \qquad (i = 1, 2, \ldots, \mathrm{N}) \tag{6.6}$$

An aging failure can be modeled using a normal distribution or a Weibull distribution. If it is modeled by a normal distribution, the integration in Equation 6.6 does not have an explicit analytical expression. A polynomial approximation [19] can be used as follows:

$$P_i = \frac{Q\left(\frac{T+(i-1)\Delta x - \mu}{\sigma}\right) - Q\left(\frac{T+i\Delta x - \mu}{\sigma}\right)}{Q\left(\frac{T-\mu}{\sigma}\right)} \qquad (i = 1, 2, \ldots, \mathrm{N}) \tag{6.7}$$

where μ and σ are the mean and standard deviation of the normal distribution and the function Q is calculated by

$$Q(y) = \begin{cases} w(y) & if\ y \geq 0 \\ 1 - w(-y) & if\ y \leq 0 \end{cases}$$

$$w(y) = z(y)(b_1 s + b_2 s^2 + b_3 s^3 + b_4 s^4 + b_s s^5)$$

$$z(y) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{y^2}{2} \right)$$

$$s = \frac{1}{1 + ry}$$

$$r = 0.2316419, \qquad b_1 = 0.31938153,$$

$$b_2 = -0.356563782, \qquad b_3 = 1.781477937,$$

$$b_4 = -1.821255978, \qquad b_5 = 1.330274429.$$

If the aging failure is modeled by a Weibull distribution, Equation 6.6 becomes

$$P_i = \frac{\exp\left(-\left(\frac{T + (i-1)\Delta x}{\alpha} \right)^{\beta} \right) - \exp\left(-\left(\frac{T + i\Delta x}{\alpha} \right)^{\beta} \right)}{\exp\left(-\left(\frac{T}{\alpha} \right)^{\beta} \right)} \quad (i = 1, 2, \ldots, N) \qquad (6.8)$$

where α and β are the scale and shape parameters for the Weibull distribution.

Calculation approach for the total unavailability of a transformer

The unavailability of a transformer due to aging failures in a specified year can be calculated using the above method. The next step is to calculate the total unavailability of the transformer including both the forced outage and aging failures. The total unavailability U_t of the transformer can be obtained using the following equation

$$U_t = U_r + U_a - U_r U_a \qquad (6.9)$$

where U_r and U_a are the unavailability associated with repairable and nonrepairable failures respectively.

Modifying the transformer reliability data including station related outages

The modified reliability data of a transformer can be obtained by combining the data from its independent minimal cut sets. The required equations including station related outages are as follows.

$$U_t' = U_t + U_{set1} + U_{set2} \tag{6.10}$$

Where,

$U_t^{'}$ is the modified unavailability of the transformer,

U_t is the total unavailability of the transformer including aging effects,

U_{set1} is the total unavailability of Set 1 (connected station 1),

U_{set2} is the total unavailability of Set 2 (connected station 2) if occurred.

The modified reliability data of the station component can be used as input data in the MECORE program. Method I is applied later in this chapter to incorporate transformer aging failures in a reliability evaluation of the two composite systems.

6.2.2 Method II

A station component such as a circuit breaker or bus bar is relatively easy to replace with a new one. In Method II, a component is replaced when it fails due to aging and the component outage time is its replacement time. Mathematical models and calculation approaches are presented for station components such as circuit breakers and bus bars including aging failures. Approximate approaches are also developed in order to simply incorporate station component aging failures in composite system reliability assessment.

It is assumed that the aging failure rates of station components such as bus bars and circuit breakers increase linearly with time. The failure density function in this case is a Weibull distribution with a shape factor of two. The time-dependent failure rate function for station components is expressed by Equation 6.11 and shown in Figure 6.2. In this equation, k is the slope factor and t_u is the useful life. The value of the slope factor is affected by a variety of factors such as mechanical design, loading, maintenance policies and environmental issues.

$$\lambda = \begin{cases} \lambda & (t \le t_u) \\ \lambda + \dfrac{\lambda \cdot k \cdot (t - t_u)}{t_u} & (t \ge t_u, k > 0) \end{cases} \tag{6.11}$$

The reliability of a composite system is evaluated on a yearly basis and annual reliability indices are used to represent system reliability performance. A one-year period is divided into N equal intervals, each with a length Δt. It is assumed that Δt is small enough that the failure rate within Δt is a constant. If the age of the component is T years

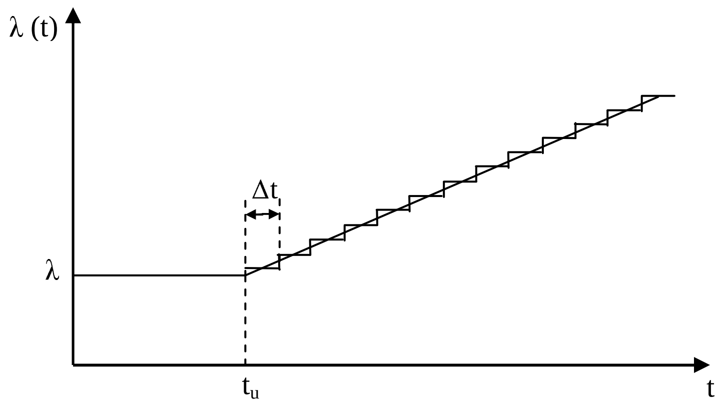

Figure 6.2: Failure rate function of a station component

and greater than t_u, then the aging failure rate in the nth interval is given by

$$\lambda_{an} = \frac{\lambda \cdot k \cdot (t - t_u)}{t_u} = \frac{\lambda \cdot k \cdot (T + (n - 1/2) \cdot \Delta t - t_u)}{t_u} \quad (n=1, 2, \ldots, N) \qquad (6.12)$$

The average aging failure rate of the component in the (T+1) year can be expressed by

$$\lambda_a = \frac{1}{N} \cdot \sum_{n=1}^{N} \frac{\lambda \cdot k \cdot (T + (n - 1/2) \cdot \Delta t - t_u)}{t_u}$$

Since the component aging failure rate function is linear when the age is greater than t_u, the aging failure rate in the (T+1) year for the T-year component is equal to the average value for the year.

$$\lambda_a = \frac{1}{N} \cdot \sum_{i=1}^{N} \frac{\lambda \cdot k \cdot (T + (i - 1/2) \cdot \Delta t - t_u)}{t_u} = \frac{\lambda \cdot k \cdot (T - 1/2 - t_u)}{t_u} \qquad (6.13)$$

(a) Accurate evaluation process

Using Equation 6.13, the component aging failure rate in each year can be represented by a constant when the component age T is greater than the useful life t_u. Mathematical models and calculation approaches are presented for bus bars and circuit breakers including aging failures.

State space model for a bus bar

The state space model for a bus bar in the ith year can be represented by Figure 6.3. The transition rate λ_b is the forced outage rate, and the transition rate μ_b is the repair rate. The transition rate λ_{ai} is the component failure rate due to aging in the ith year obtained using Equation 6.13, and the transition rate μ_a is the replacement rate. Preventive maintenance is not included since it is not performed on bus bars.

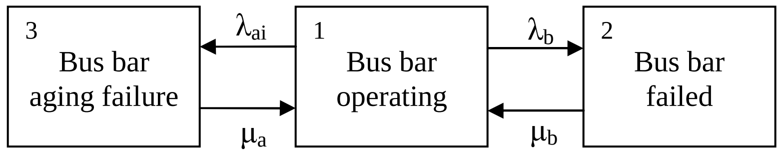

Figure 6.3: Three-state model of a bus bar in the *i*th year

This three-state model can be reduced to a two-state model as shown in Figure 6.4 by combining states 2 and 3.

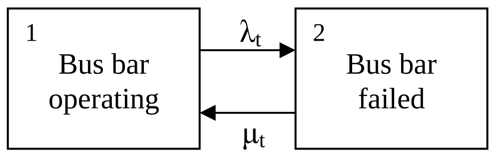

Figure 6.4: Reduced model of a bus bar in the *i*th year

The frequency balance approach can be used to calculate the state probabilities and transition rates between states in Figures 6.3 and 6.4. The basic concept in this approach is that for any state in the system the expected frequency of leaving a state must equal the expected frequency of entering the state. The following equations can be obtained using this approach.

$$\begin{aligned} P_1 \cdot \lambda_b &= P_2 \cdot \mu_b \\ P_1 \cdot \lambda_{ai} &= P_3 \cdot \mu_a \\ P_1 + P_2 + P_3 &= 1 \end{aligned}$$

Solving the above equations,

$$\begin{aligned} P_1 &= \frac{\mu_a \mu_b}{\lambda_{ai}\mu_b + \lambda_b \mu_a + \mu_a \mu_b} \\ P_2 &= \frac{\lambda_b \mu_a}{\lambda_{ai}\mu_b + \lambda_b \mu_a + \mu_a \mu_b} \\ P_3 &= \frac{\lambda_{ai} \mu_b}{\lambda_{ai}\mu_b + \lambda_b \mu_a + \mu_a \mu_b} \end{aligned} \tag{6.14}$$

The total availability and unavailability of the bus bar in Figure 6.4 is calculated by

$$\begin{aligned} A_t &= P_1 = \frac{\mu_a \mu_b}{\lambda_{ai}\mu_b + \lambda_b \mu_a + \mu_a \mu_b} \\ U_t &= P_2 + P_3 = \frac{\lambda_{ai}\mu_b + \lambda_b \mu_a}{\lambda_{ai}\mu_b + \lambda_b \mu_a + \mu_a \mu_b} \end{aligned} \tag{6.15}$$

The equivalent failure rate and the repair rate in the ith year are

$$\lambda_t = \lambda_{ai} + \lambda_b$$
$$\mu_t = \frac{A_t \lambda_t}{U_t} = \frac{\mu_a \mu_b \cdot (\lambda_{ai} + \lambda_b)}{\lambda_{ai}\mu_b + \lambda_b \mu_a} \tag{6.16}$$

The equivalent repair time in the ith year is

$$r_t = \frac{1}{\mu_t} = \frac{\lambda_{ai}\mu_b + \lambda_b \mu_a}{\mu_a \mu_b \cdot (\lambda_{ai} + \lambda_b)} \tag{6.17}$$

State space model for a circuit breaker

The state space model for a circuit breaker in the ith year can be represented by Figure 6.5. The transition rates λ_{aai} and λ_{api} are the active failure rate and passive failure rate due to aging in the ith year respectively. The transition rate μ_a is the replacement rate of the circuit breaker and μ_{asw} is the switching rate which is assumed to equal μ_{sw}. Preventive maintenance is not included in this model.

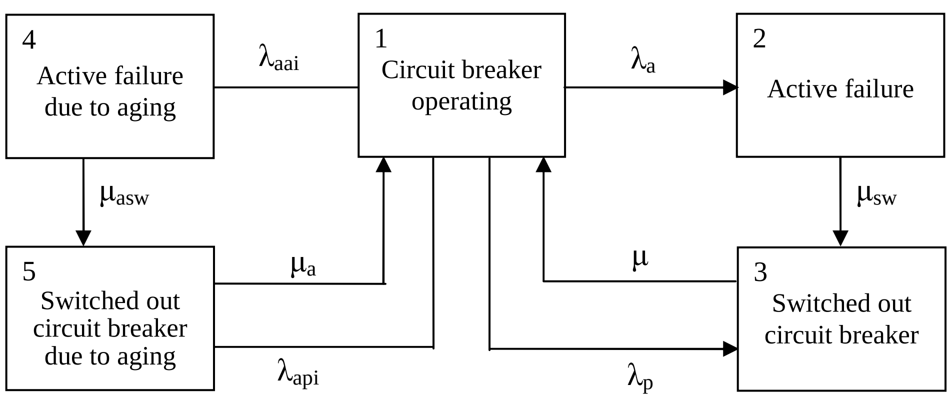

Figure 6.5: Model of a circuit breaker in the ith year

The aging failure rate λ_{ai} in the ith year can be obtained using Equation 6.13. The ratio of active failures of a circuit breaker due to aging over related passive failures is assumed to be nine, which is the same as that used under normal conditions.

The active failure rate λ_{aai} and passive failure rate λ_{api} is obtained as follows.

$$\lambda_{aai} = 0.9 \cdot \lambda_{ai}$$
$$\lambda_{api} = 0.1 \cdot \lambda_{ai} \tag{6.18}$$

The frequency balance approach can by used to calculate the state probabilities in Figure 6.5.

$$
\begin{aligned}
&P_1 \cdot \lambda_a = P_2 \cdot \mu_{sw} \\
&P_1 \cdot \lambda_p + P_2 \cdot \mu_{sw} = P_3 \cdot \mu \\
&P_1 \cdot \lambda_{aai} = P_4 \cdot \mu_{asw} \\
&P_1 \cdot \lambda_{api} + P_4 \cdot \mu_{asw} = P_5 \cdot \mu_a \\
&P_1 + P_2 + P_3 + P_4 + P_5 = 1
\end{aligned}
$$

Solving the above equations,

$$
\begin{aligned}
&P_1 = \frac{\mu \cdot \mu_a \cdot \mu_{sw} \cdot \mu_{asw}}{D} \\
&P_2 = \frac{\lambda_a \cdot \mu \cdot \mu_a \cdot \mu_{asw}}{D} \\
&P_3 = \frac{(\lambda_a + \lambda_p) \cdot \mu_a \cdot \mu_{sw} \cdot \mu_{asw}}{D} \\
&P_4 = \frac{\lambda_{aai} \cdot \mu \cdot \mu_a \cdot \mu_{sw}}{D} \\
&P_5 = \frac{(\lambda_{aai} + \lambda_{api}) \cdot \mu \cdot \mu_{sw} \cdot \mu_{asw}}{D}
\end{aligned}
\tag{6.19}
$$

where

$$
\begin{aligned}
D = {} & \lambda_a(\mu \cdot \mu_a \cdot \mu_{asw} + \mu_a \cdot \mu_{sw} \cdot \mu_{asw}) + \lambda_p \cdot \mu_a \cdot \mu_{sw} \cdot \mu_{asw} + \lambda_{aai}(\mu \cdot \mu_a \cdot \mu_{sw} + \mu \cdot \mu_{sw} \cdot \mu_{asw}) \\
& + \lambda_{api} \cdot \mu \cdot \mu_{sw} \cdot \mu_{asw} + \mu \cdot \mu_a \cdot \mu_{sw} \cdot \mu_{asw}
\end{aligned}
$$

The five-state model can be reduced to the three-state model shown in Figure 6.6 by combining states 2 and 4, and states 3 and 5. The transition rates λ_{at} and λ_{pt} are the equivalent active failure rate and passive failure rate in the *i*th year respectively. The transition rate μ_t is the equivalent repair rate of the circuit breaker and μ_{swt} is the equivalent switching rate in the *i*th year.

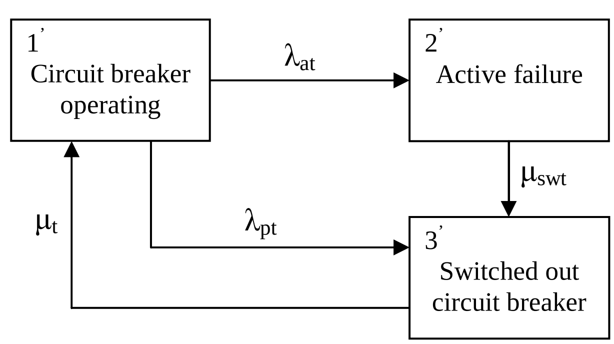

Figure 6.6: Reduced model of a circuit breaker in the *i*th year

The state probabilities in Figure 6.6 can be calculated by

$$\mathrm{P}_1^{'} = \mathrm{P}_1$$
$$\mathrm{P}_2^{'} = \mathrm{P}_2 + \mathrm{P}_4$$
$$\mathrm{P}_3^{'} = \mathrm{P}_3 + \mathrm{P}_5$$

The total availability and unavailability of the circuit breaker in Figure 6.6 is given by

$$\begin{aligned} \mathrm{A}_t &= \mathrm{P}_1' = \frac{\mu \cdot \mu_a \cdot \mu_{sw} \cdot \mu_{asw}}{D} \\ U_t &= 1 - \mathrm{P}_1' = 1 - \frac{\mu \cdot \mu_a \cdot \mu_{sw} \cdot \mu_{asw}}{D} \end{aligned} \tag{6.20}$$

The frequency of encountering the cumulative state $2^{'}$ in Figure 6.6 is

$$f_2^{'} = f_{24} = f_2 + f_4 - (\mathit{frequency\ \ of\ \ encounters\ \ between}\ \ 2\ \ \mathit{and}\ \ 4)$$
$$\mathrm{P}_2^{'} \cdot \mu_{swt} = \mathrm{P}_2 \cdot \mu_{sw} + \mathrm{P}_4 \cdot \mu_{asw}$$

The equivalent switching rate in the *i*th year can be calculated as follows.

$$\begin{aligned} \mu_{swt} &= \frac{\mathrm{P}_2 \cdot \mu_{sw} + \mathrm{P}_4 \cdot \mu_{asw}}{\mathrm{P}_2^{'}} = \frac{\mathrm{P}_2 \cdot \mu_{sw} + \mathrm{P}_4 \cdot \mu_{asw}}{\mathrm{P}_2 + \mathrm{P}_4} \\ &= \frac{(\lambda_a + \lambda_{aai}) \cdot \mu \cdot \mu_a \cdot \mu_{sw} \cdot \mu_{asw}}{\lambda_a \cdot \mu \cdot \mu_a \cdot \mu_{asw} + \lambda_{aai} \cdot \mu \cdot \mu_a \cdot \mu_{sw}} \\ &= \frac{(\lambda_a + \lambda_{aai}) \cdot \mu_{sw} \cdot \mu_{asw}}{\lambda_a \cdot \mu_{asw} + \lambda_{aai} \cdot \mu_{sw}} \end{aligned} \tag{6.21}$$

The frequency of encountering the cumulative state $3^{'}$ in Figure 6.6 is

$$f_3^{'} = f_{35} = f_3 + f_5 - (\mathit{frequency\ \ of\ \ encounters\ \ between}\ \ 3\ \ \mathit{and}\ \ 5)$$
$$\mathrm{P}_3^{'} \cdot \mu_t = \mathrm{P}_3 \cdot \mu + \mathrm{P}_5 \cdot \mu_a$$

The equivalent repair rate in the *i*th year can be calculated as follows.

$$\begin{aligned} \mu_t &= \frac{\mathrm{P}_3 \cdot \mu + \mathrm{P}_5 \cdot \mu_a}{\mathrm{P}_3^{'}} = \frac{\mathrm{P}_3 \cdot \mu + \mathrm{P}_5 \cdot \mu_a}{\mathrm{P}_3 + \mathrm{P}_5} \\ &= \frac{(\lambda_a + \lambda_p + \lambda_{aai} + \lambda_{api}) \cdot \mu \cdot \mu_a \cdot \mu_{sw} \cdot \mu_{asw}}{(\lambda_a + \lambda_p) \cdot \mu_a \cdot \mu_{sw} \cdot \mu_{asw} + (\lambda_{aai} + \lambda_{api}) \cdot \mu \cdot \mu_{sw} \cdot \mu_{asw}} \\ &= \frac{(\lambda_a + \lambda_p + \lambda_{aai} + \lambda_{api}) \cdot \mu \cdot \mu_a}{(\lambda_a + \lambda_p) \cdot \mu_a + (\lambda_{aai} + \lambda_{api}) \cdot \mu} \end{aligned} \tag{6.22}$$

The frequency of entering state $2^{'}$ in Figure 6.6 is equal to the frequency of leaving the same state. The equivalent active failure rate in the *i*th year is obtained as follows.

$$
\begin{aligned}
&P_2' \cdot \mu_{swt} = P_1' \cdot \lambda_{at} \\
&\therefore \lambda_{at} = \frac{P_2' \cdot \mu_{swt}}{P_1'} \\
&\quad = \left(\frac{\lambda_a}{\mu_{sw}} + \frac{\lambda_{aai}}{\mu_{asw}} \right) \cdot \frac{(\lambda_a + \lambda_{aai}) \cdot \mu_{sw} \cdot \mu_{asw}}{\lambda_a \cdot \mu_{asw} + \lambda_{aai} \cdot \mu_{sw}} \\
&\quad = \frac{(\lambda_a + \lambda_{aai}) \cdot (\lambda_a \cdot \mu_{asw} + \lambda_{aai} \cdot \mu_{sw})}{\lambda_a \cdot \mu_{asw} + \lambda_{aai} \cdot \mu_{sw}} \\
&\quad = \lambda_a + \lambda_{aai}
\end{aligned}
\tag{6.23}
$$

The frequency of entering state 1' in Figure 6.6 is equal to the frequency of leaving the same state. The equivalent passive failure rate in the *i*th year is obtained as follows.

$$
\begin{aligned}
&P_1' \cdot (\lambda_{at} + \lambda_{pt}) = P_3' \cdot \mu_t \\
&\lambda_{pt} = \frac{P_3' \cdot \mu_t - P_1' \cdot \lambda_{at}}{P_1'} \\
&\quad = \left(\frac{\lambda_a + \lambda_p}{\mu} + \frac{\lambda_{aai} + \lambda_{api}}{\mu_a} \right) \cdot \mu_t - \lambda_{at} \\
&\quad = \left(\frac{\lambda_a + \lambda_p}{\mu} + \frac{\lambda_{aai} + \lambda_{api}}{\mu_a} \right) \cdot \frac{(\lambda_a + \lambda_p + \lambda_{aai} + \lambda_{api}) \cdot \mu \cdot \mu_a}{(\lambda_a + \lambda_p) \cdot \mu_a + (\lambda_{aai} + \lambda_{api}) \cdot \mu} - (\lambda_a + \lambda_{aai}) \\
&\quad = \big((\lambda_a + \lambda_p) \cdot \mu_a + (\lambda_{aai} + \lambda_{api}) \cdot \mu\big) \cdot \frac{(\lambda_a + \lambda_p + \lambda_{aai} + \lambda_{api})}{(\lambda_a + \lambda_p) \cdot \mu_a + (\lambda_{aai} + \lambda_{api}) \cdot \mu} - (\lambda_a + \lambda_{aai}) \\
&\quad = \lambda_p + \lambda_{api}
\end{aligned}
\tag{6.24}
$$

The equivalent repair time in the *i*th year is given by

$$
r_t = \frac{1}{\mu_t} = \frac{(\lambda_a + \lambda_p) \cdot \mu_a + (\lambda_{aai} + \lambda_{api}) \cdot \mu}{(\lambda_a + \lambda_p + \lambda_{aai} + \lambda_{api}) \cdot \mu \cdot \mu_a} \tag{6.25}
$$

The equivalent switching time in the *i*th year is given by

$$
r_{swt} = \frac{1}{\mu_{swt}} = \frac{\lambda_a \cdot \mu_{asw} + \lambda_{aai} \cdot \mu_{sw}}{(\lambda_a + \lambda_{aai}) \cdot \mu_{sw} \cdot \mu_{asw}} \tag{6.26}
$$

(b) Approximate evaluation process

Approximate method for a bus bar

The state space model for a bus bar in the *i*th year is shown in Figure 6.3. The three-state model can be reduced to the two-state model shown in Figure 6.4 by combining states 2 and 3.

The total failure rate of the bus bar in the *i*th year can be obtained by

$$\lambda_t = \lambda + \lambda_{ai} \tag{6.27}$$

The total unavailability of the bus bar in the *i*th year is calculated approximately by

$$U_t = \lambda \cdot \frac{1}{\mu} + \lambda_{ai} \cdot \frac{1}{\mu_a} \tag{6.28}$$

The equivalent repair time in the *i*th year is

$$r_t = \frac{U_t}{\lambda_t} = \frac{U_t}{\lambda + \lambda_{ai}} \tag{6.29}$$

Equations 6.27-6.29 can be compared with Equations 6.15-6.17.

Approximate method for a circuit breaker

The state space model for a circuit breaker in the *i*th year is shown in Figure 6.5. The aging failure rate λ_{ai} for the circuit breaker in the *i*th year can be calculated using Equation 6.13.

The approximate method was developed in order to more easily evaluate the circuit breaker reliability parameters. In this procedure, the active failures and the passive failures of a circuit breaker due to random failures or aging are grouped separately. States 2 and 3 are grouped and states 4 and 5 in Figure 6.5 are grouped. The switching action of the circuit breaker is not considered, since the switching time is very short. The five-state model is then reduced to the three-state model in Figure 6.7. The transition rates λ_{ai} and μ_a are the total failure rate and replacement rate of the circuit breaker due to aging in the *i*th year respectively. The transition rate λ and μ is the total forced outage rate and repair rate of the circuit breaker.

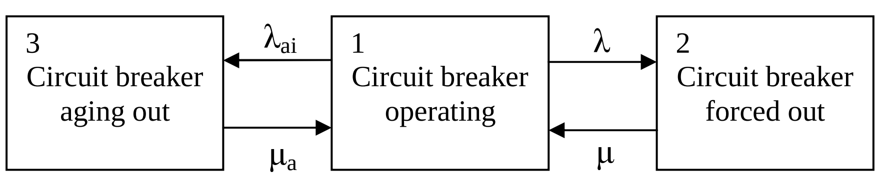

Figure 6.7: Approximate model of a circuit breaker in the *i*th year

The three-state model can be reduced to the two-state model shown in Figure 6.8 by combining states 2 and 3.

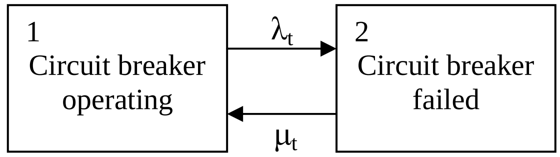

Figure 6.8: Reduced approximate model of a circuit breaker in the *i*th year

The total failure rate of the circuit breaker is

$$\lambda_t = \lambda + \lambda_{ai} \tag{6.30}$$

The total unavailability of the breaker is

$$U_t = \lambda \cdot \frac{1}{\mu} + \lambda_{ai} \cdot \frac{1}{\mu_a} \tag{6.31}$$

The equivalent repair time is

$$r_t = \frac{U_t}{\lambda_t} = \frac{U_t}{\lambda + \lambda_{ai}} = \frac{\lambda \cdot \frac{1}{\mu} + \lambda_{ai} \cdot \frac{1}{\mu_a}}{\lambda + \lambda_{ai}} = \frac{\lambda \cdot \mu_a + \lambda_{ai} \cdot \mu}{(\lambda + \lambda_{ai}) \cdot \mu \cdot \mu_a} \tag{6.32}$$

The equivalent repair rate is

$$\mu_t = \frac{1}{r_t} = \frac{(\lambda + \lambda_{ai}) \cdot \mu \cdot \mu_a}{\lambda \cdot \mu_a + \lambda_{ai} \cdot \mu} \tag{6.33}$$

Once these reliability parameters are obtained, the next step is to separate the active and passive failures of the circuit breaker. The switching action of a circuit breaker is now taken into consideration. The state space model shown as Figure 6.9 is the same as in Figure 6.6 but the transition rates are different. The transition rates λ_{at} and λ_{pt} are the equivalent active failure rate and passive failure rate in the *i*th year respectively. The transition rate μ_t is the equivalent repair rate of the circuit breaker and μ_{swt} is the equivalent switching rate in the *i*th year.

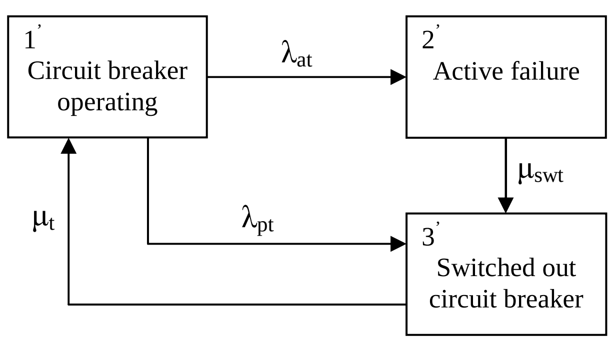

Figure 6.9: Approximate state space model of a circuit breaker in the *i*th year

The total active failure rate and passive failure rate of the circuit breaker is obtained as follows.

$$\begin{aligned} \lambda_{at} &= 0.9 \cdot \lambda_t = 0.9 \cdot (\lambda + \lambda_{ai}) = \lambda_a + \lambda_{aai} \\ \lambda_{pt} &= 0.1 \cdot \lambda_t = 0.1 \cdot (\lambda + \lambda_{ai}) = \lambda_p + \lambda_{api} \end{aligned} \tag{6.34}$$

where,

$$\begin{cases} \lambda_a = 0.9 \cdot \lambda \\ \lambda_p = 0.1 \cdot \lambda \end{cases} \qquad \begin{cases} \lambda_{aai} = 0.9 \cdot \lambda_{ai} \\ \lambda_{api} = 0.1 \cdot \lambda_{ai} \end{cases}$$

The equivalent repair rate μ_t in Figure 6.9 is assumed to equal the repair rate in Figure 6.8. The equivalent repair rate and repair time can be expressed by

$$\mu_t = \frac{(\lambda + \lambda_{ai}) \cdot \mu \cdot \mu_a}{\lambda \cdot \mu_a + \lambda_{ai} \cdot \mu}$$

$$r_t = \frac{\lambda \cdot \mu_a + \lambda_{ai} \cdot \mu}{(\lambda + \lambda_{ai}) \cdot \mu \cdot \mu_a}$$

The equivalent repair time in the *i*th year is equal to

$$r_t = \frac{(\lambda_a + \lambda_p) \cdot \mu_a + (\lambda_{aai} + \lambda_{api}) \cdot \mu}{(\lambda_a + \lambda_p + \lambda_{aai} + \lambda_{api}) \cdot \mu \cdot \mu_a} \tag{6.35}$$

The equivalent switching rate is assumed to be equal to the switching rate in the normal condition.

$$\begin{aligned} \mu_{swt} &= \mu_{sw} = 8760/1 = 8760 \qquad occ/yr \\ r_{swt} &= r_{sw} = 1 \qquad hour \end{aligned} \tag{6.36}$$

The reliability parameters of a circuit breaker, such as the equivalent active failure rate, passive failure rate, repair time and switching time are used to incorporate station related outages in the composite system reliability evaluation. The equations developed in the approximate approach and those obtained by the accurate approach to calculate the equivalent active failure rate, passive failure rate and repair time are the same. The equations developed to calculate the circuit breaker unavailability are different. The equations used to calculate the circuit breaker parameters are developed under the assumption that the switching rate of circuit breaker due to aging is the same as that due to a forced outage. The equivalent switching time cannot be obtained using the approximate method.

The two different evaluation techniques to incorporate station component aging failures are described in this section. Only one reliability parameter, the component unavailability, is obtained using Method I. One important point of this method is that a component effectively disappears when it fails due to aging since aging failures are nonrepairable events. In an actual power system, however, this is not the case. When a component fails due to aging, it is restored or replaced by a new one. Method II was therefore developed to recognize this. Additional component reliability parameters can be obtained using Method II, compared with Method I. The two methods can be applied to different situations. Large transformers when they fail due to aging are difficult to remove, to obtain and to install a new one while circuit breakers and bus bars are relatively easy to replace. Method I can be applied to incorporate transformer aging failures in composite system adequacy assessment. On the other hand, Method II can be utilized to incorporate circuit breaker and bus bar aging failures in station analysis.

6.3 Applications of Method I to Composite System Reliability Evaluation

Method I is applied to incorporate transformer aging failures in the reliability assessment of the two composite test systems. The transformer unavailability due to aging failures in a specified year can be calculated using either the normal distribution or the Weibull distribution. The transformer mean life and standard deviation are assumed to be the same in the two models in order to compare the results obtained. The characteristic parameters, α and β of the Weibull distribution are calculated based on this data. The calculation process is shown in Appendix F. Computer programs have been developed to calculate transformer unavailability due to aging failures using the two models. Transformer maintenance outages are not included in the following analyses.

6.3.1 Incorporating Station Transformer Aging Failures in the Modified RBTS

The single line diagram of the modified RBTS with ring bus configurations is shown in Figure 4.11. Aging failures are considered for the transformers at Station 2. The mean life of the transformers is assumed to be 45 years with a standard deviation of 10 years. The transformer unavailability due to aging failures in a specified year was calculated using the normal and Weibull distribution models and transformer unavailabilities obtained using the two models are compared.

Incorporating transformer aging failures using the normal distribution model

The normal distribution model is used to calculate the transformer unavailability due to aging failures. The age of the transformers at Station 2 is assumed to be 10 years, 20 years, ..., 50 years respectively to examine the relative aging effects. Table 6.1 shows the unavailability of the transformers at Station 2 including aging failures for a one year period at different ages. It can be seen from this table that the transformer unavailability due to aging failures increases rapidly as the transformer ages. The unavailability due to transformer repairable failures is constant and independent of its age. The total unavailability due to component repairable and nonrepairable failures increases as the component age increases.

Table 6.1: Unavailability of the transformers at Station 2 for a one year period (Normal model)

Age (yr)	Unavailability (Repairable)	Unavailability (Aging-Normal)	Transformer unavailability
10	0.001753	0.000049	0.001802
20	0.001753	0.000959	0.002710
30	0.001753	0.007294	0.009034
40	0.001753	0.025866	0.027574
50	0.001753	0.056069	0.057724

Figure 6.10 shows the load point and system EENS as a function of the transformer age using the normal distribution model.

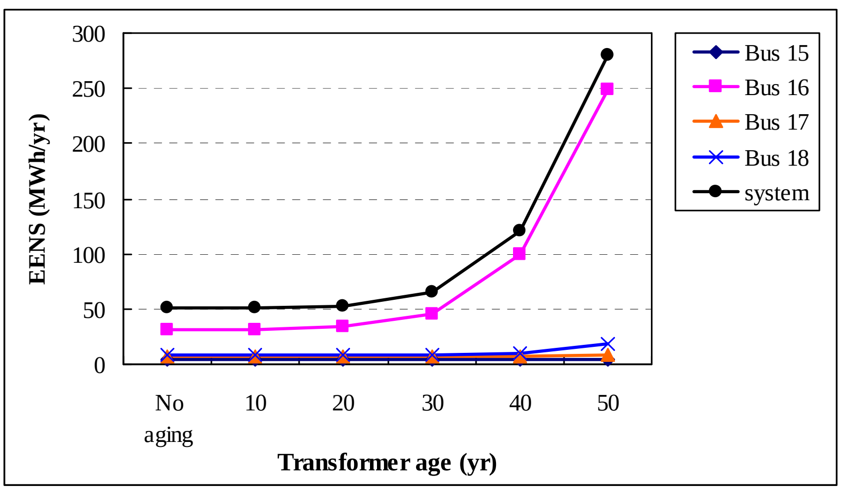

Figure 6.10: Load point and the modified RBTS EENS as a function of the transformer age (Normal model)

It can be seen from this figure that the load point and system EENS increase very slowly when the transformers are early in their life. The load point EENS at Station 3 increases rapidly as transformers approach their mean life of 45 years. Station 3 is the heaviest load point in the system and has the lowest priority. The load points and system reliability degrade more rapidly when the transformer age exceeds its mean life. When the transformers are 50 years old, the total system EENS is over five times greater than the EENS without considering aging failures.

Incorporating transformer aging failures using the Weibull distribution model

The Weibull distribution model was used to calculate the transformer unavailability due to aging failures. Table 6.2 shows the transformer unavailability including aging failures for a one year period at different age levels. It can be seen from this table that the transformer unavailability due to aging failures increases as the transformer ages. The load point and system EENS as a function of the transformer age are shown in Figure 6.11. The EENS profiles are very similar to those obtained using the normal distribution model.

Table 6.2: Unavailability of the transformers at Station 2 for a one year period (Weibull model)

Age (yr)	Unavailability (Repairable)	Unavailability (Aging-Weibull)	Transformer unavailability
10	0.001753	0.000115	0.001868
20	0.001753	0.001732	0.003482
30	0.001753	0.008570	0.010308
40	0.001753	0.026529	0.028235
50	0.001753	0.062850	0.064493

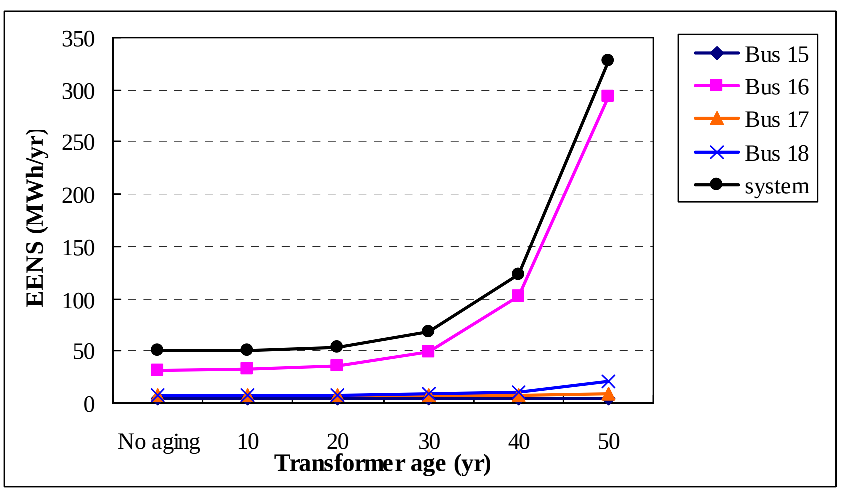

Figure 6.11: Load point and the modified RBTS EENS as a function of the transformer age (Weibull model)

Reliability comparison using the two different models

A comparison of the transformer unavailability due to aging failures obtained using the two models are shown in Figure 6.12. The unavailability due to aging failures using the Weibull distribution model is a little larger than that obtained using the normal distribution model.

The load point and system EENS obtained using the two different models with the same mean life and standard deviation are compared and shown in Figure 6.13. The load point and system EENS obtained using the Weibull distribution model are higher than those obtained using the normal distribution model, particularly when the components are close to their mean life.

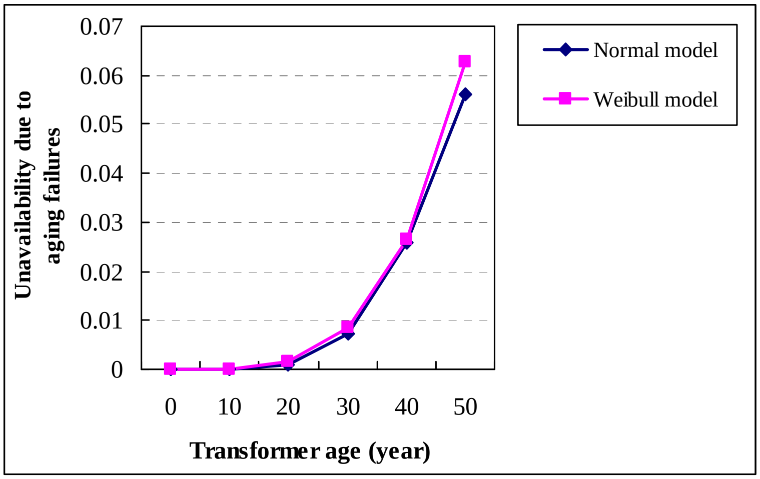

Figure 6.12: Unavailability due to aging failures for the transformers at Station 2 as a function of the transformer age

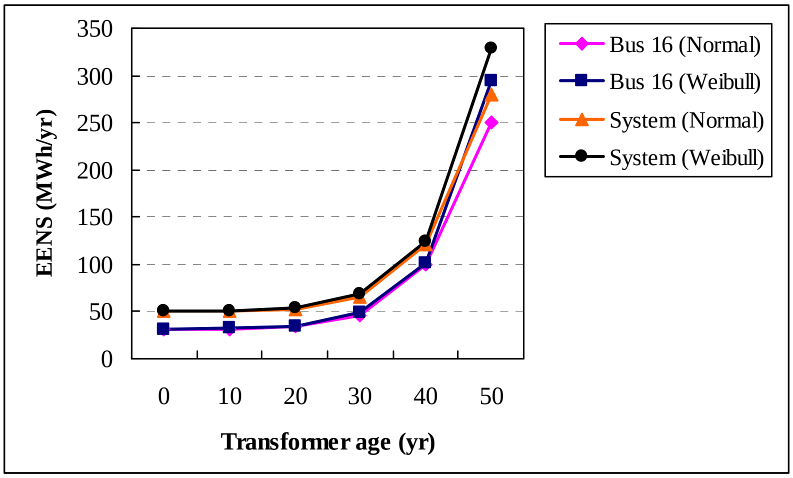

Figure 6.13: Load point EENS at Station 3 and the RBTS EENS comparison as a function of the transformer age

6.3.2 Incorporating Station Transformer Aging Failures in the IEEE-RTS

Transformer aging failures were incorporated in a reliability evaluation of the IEEE-RTS with ring bus configurations, using the normal distribution model and Weibull distribution model. The single line diagram of the IEEE-RTS with ring bus schemes is shown in Figure 4.18. Aging failures are first considered in the single transformer at Station 18, which has the largest capacity generator in the IEEE-RTS and then considered in the five transmission transformers connecting the 138kV and the 230kV sides of the IEEE-RTS.

(a) Considering aging failures in a generating unit transformer

Aging failures of the generating unit transformer in Station 18 were incorporated in an IEEE-RTS reliability evaluation. The transformer unavailability due to aging failures in a specified year was calculated using the normal distribution model and the Weibull distribution model. The mean life of the transformer is assumed to be 45 years with a standard deviation of 10 years. The transformer unavailability and the selected load point and system reliability indices obtained using the two models are compared.

Incorporating transformer aging failures using the normal distribution model

The unavailability of the generating unit transformer at Station 18 including aging failure for a one year period at different age levels using the normal distribution model are shown in Table 6.3. Figure 6.14 shows the load point EENS at Buses 44, 51, 61 and 62 (Stations 9, 15, 18 and 19) and the system EENS as a function of the transformer age.

Table 6.3: Unavailability of the transformer at Station 18 for a one year period (Normal model)

Age (yr)	Unavailability (Repairable)	Unavailability (Aging-Normal)	Total Unavailability
10	0.002371	0.000049	0.002420
20	0.002371	0.000959	0.003328
30	0.002371	0.007294	0.009648
40	0.002371	0.025866	0.028176
50	0.002371	0.056069	0.058307

The transformer unavailability due to aging failures increases as the transformer ages. The variations in the transformer failure rate have effects not only on the load point at Station 18 but also on the load points at other stations. Stations 9, 15, 18 and 19 are affected the most by aging failures of the transformer in Station 18. Transformer aging

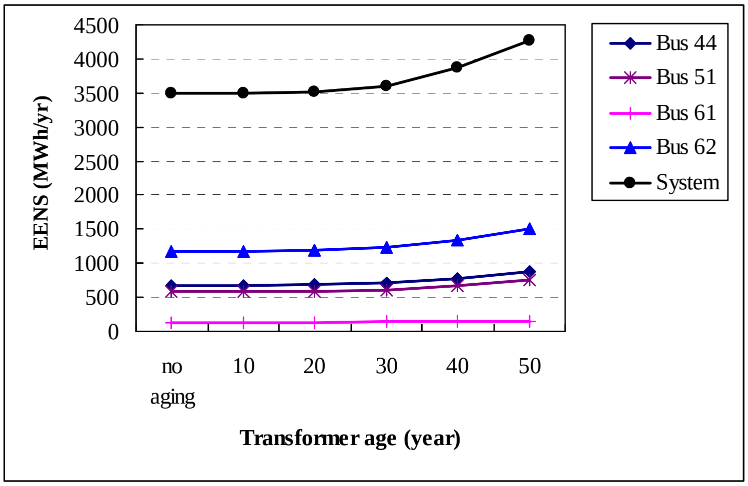

Figure 6.14: Load point and the IEEE-RTS EENS as a function of the transformer age (Normal model)

failures have relatively little effect on the load point and system EENS when the transformer is at an early point in its life. The effects of transformer aging failures on the load point and system EENS, however, increase quickly as the transformer approaches its mean life of 45 years. The IEEE-RTS has a relatively weak generation system. As a result, the incorporation of aging failures in only one generating unit transformer has a significant effect on the load point and system reliability.

Incorporating transformer aging failures using the Weibull distribution model

The Weibull distribution model was used to calculate the transformer unavailability due to aging failures. The transformer unavailability including aging failures for a one year period at different age levels is shown in Table 6.4. Figure 6.15 shows the EENS at Buses 44, 51, 61 and 62 (Stations 9, 15, 18 and 19) and system EENS as a function of the transformer age. The EENS profiles are very similar to those obtained using the normal distribution model.

Table 6.4: Unavailability of the transformer in Station 18 for a one year period (Weibull model)

Age (yr)	Unavailability (Repairable)	Unavailability (Aging-Weibull)	Total Unavailability
10	0.002371	0.000115	0.002486
20	0.002371	0.001732	0.004099
30	0.002371	0.008570	0.010921
40	0.002371	0.026529	0.028837
50	0.002371	0.062850	0.065072

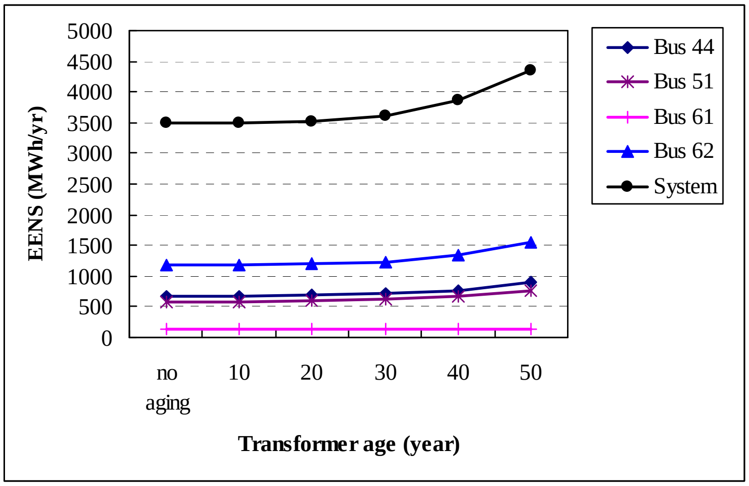

Figure 6.15: Load point and the IEEE-RTS EENS as a function of the transformer age (Weibull model)

Reliability comparison using the two different models

A comparison of the transformer unavailability due to aging failures and the system EENS obtained using the two models are shown in Figures 6.16 and 6.17 respectively.

It can be seen that the unavailability of aging failures using the Weibull distribution model is a little larger than that obtained using the normal distribution model. The system EENS obtained using the Weibull distribution model is higher than that obtained using the normal distribution model, particularly when the transformer is close to its mean life.

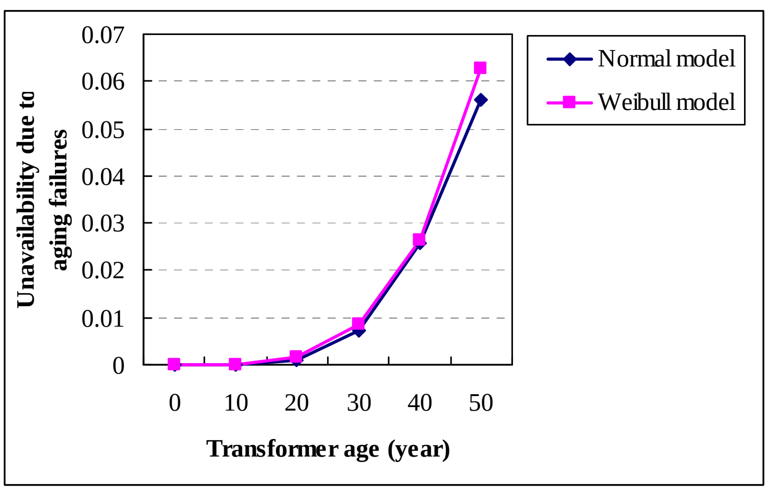

Figure 6.16: Unavailability due to aging failures for the transformer at Station 18 as a function of the transformer age

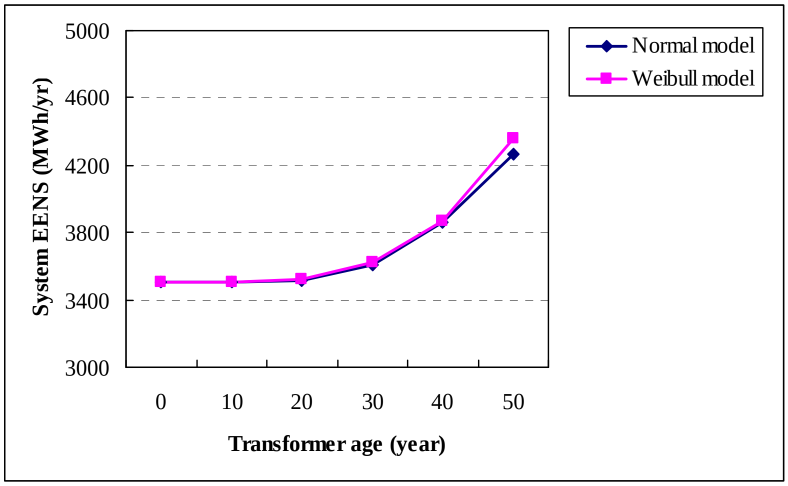

Figure 6.17: The IEEE-RTS EENS comparison as a function of the transformer age

(b) Considering aging failures of the five transmission transformers

Aging failures of the five transmission transformers connecting the 138kV and the 230kV sides of the IEEE-RTS were incorporated in a reliability evaluation of the IEEE-RTS with ring bus configurations. The mean life of all the transformers is assumed to be 45 years with a standard deviation of 10 years. The age of the five transformers is assumed to be 50 years in order to examine extreme aging effects. Previous studies show that the effects of component aging failures on the load point and system reliability are greater when using the Weibull distribution model than those obtained using the normal distribution model. The Weibull distribution model is therefore used to evaluate the transformer unavailability due to aging failures. The transformer unavailability and system reliability indices are shown in the following.

Table 6.5 shows the transformer unavailabilities including aging failures for a one year period using the Weibull distribution model. The annual load point and system EENS without and with transmission transformer aging failures for the IEEE-RTS with ring bus schemes are shown in Table 6.6.

Table 6.5: Unavailability of transmission transformers including aging failures (Weibull model)

Transformer ID	Unavailability (Repairable)	Unavailability (Aging-Normal)	Transformer unavailability
Line 7	0.00175	0.06285	0.064490
Line 14	0.002336	0.06285	0.065039
Line 15	0.002336	0.06285	0.065039
Line 16	0.002336	0.06285	0.065039
Line 17	0.002336	0.06285	0.065039

Table 6.6: Annual load point and system EENS without and with transmission transformer aging failures for the IEEE-RTS with ring bus schemes

Station No.	Bus No.	EENS (MWh/yr)	EENS (Aging)	Increase rate (%)
1	29	35.098	35.107	0.03
2	34	32.902	33.276	1.12
3	35	66.718	67.305	0.87
4	36	34.000	34.009	0.03
5	37	36.601	37.078	1.29
6	38	76.204	76.349	0.19
7	39	64.437	64.619	0.28
8	43	72.822	74.250	1.92
9	44	677.202	684.005	0.99
10	45	98.168	101.109	2.91
13	49	115.839	115.839	0.00
14	50	164.147	164.159	0.01
15	51	588.645	588.618	0.00
16	59	61.755	61.754	0.00
18	61	135.568	135.568	0.00
19	62	1182.101	1181.983	-0.01
20	63	62.223	62.222	0.00
System		3504.423	3515.233	0.36

The transformer unavailabilities due to aging failures are much larger than those due to random failures. The actual unavailabilities of the five transmission transformers increase considerably by including aging failures. It can be seen from Table 6.6 that aging failures of these five transmission transformers have relatively little effect on the load point and system EENS. This further indicates that the IEEE-RTS has a strong transmission system.

6.4 Application of Method II to Composite System Reliability Evaluation

Accurate and approximate evaluation processes were developed in Method II to calculate the station component reliability parameters including aging failures. The two approaches were applied to determine the required circuit breaker and bus bar data. These parameters were then used as input data to evaluate the aging effects of related components on the reliability performance of the modified RBTS. Circuit breaker and transformer maintenance outages are considered in the following analyses.

6.4.1 Incorporating Bus Bar Aging Failures in the Modified RBTS

Aging failures of bus bars are incorporated in the reliability evaluation of the modified RBTS with ring bus configurations shown in Figure 4.11. It is assumed that the bus bar failure rates follow Equation 6.11 and the profile shown in Figure 6.2. The useful life of bus bars is assumed to be thirty years and the replacement time of a bus bar is assumed to be six days. It is also assumed that bus bars at Station 2 are over 30 years old while the bus bars in other stations are within their useful life. Aging failures of the bus bars at Station 2 are incorporated in the reliability evaluation.

The equivalent failure rate, repair time and the unavailability of the bus bars at Station 2 can be calculated using the equations developed earlier. The slope factor k is assumed to be equal to 0.5. Table 6.7 shows the reliability data for the bus bar including both random failures and aging failures as a function of bus bar age, using the accurate and approximate evaluation approaches. As noted earlier, the equivalent failure rate and repair time for the bus bar are the same using the two different approaches. The unavailability in hours per year obtained by the accurate approach is a little smaller than that obtained by the approximate approach. The difference in the unavailability for the two approaches is less than 1% and can be neglected. The approximate approach is applied in the following studies. The modified bus bar reliability data is used to examine the effects of bus bar aging failures using the minimal cut set method and the MECORE program.

Table 6.7: Reliability data for the bus bars at Station 2 for a one year period (k=0.5)

Age of bus bar (yr)	Failure rate (f/yr)	Repair time (hr)	Unavailability (hr/yr) (accurate)	Unavailability (hr/yr) (approximate)	Unavailability
<30	0.025	10	0.249993	0.25	0.000029
31	0.025208	11.107438	0.279991	0.28	0.000032
32	0.025625	13.268293	0.339987	0.34	0.000039
33	0.026042	15.360000	0.399982	0.4	0.000046
34	0.026458	17.385827	0.459976	0.46	0.000053
35	0.026875	19.348837	0.519969	0.52	0.000059

Load point EENS at Station 2 and the system EENS as a function of the bus bar age are shown in Figure 6.18. It can be seen that the load point EENS and system EENS increase slowly as the bus bars proceed into the wear-out region. The slope factor k in this case is relatively small (k=0.5).

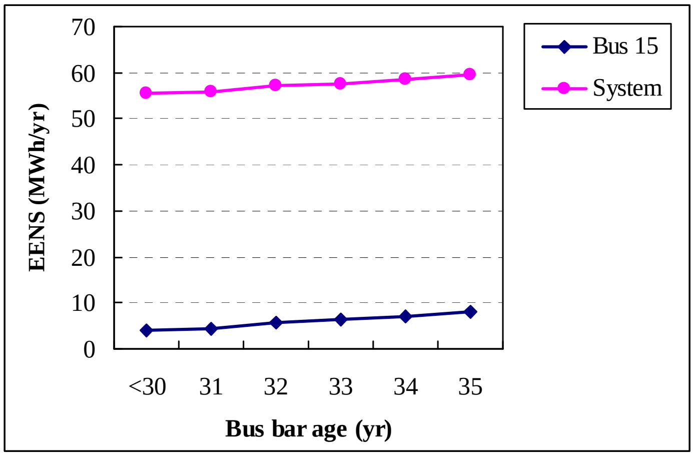

Figure 6.18: Load point EENS at Station 2 and the modified RBTS EENS as a function of the bus bar age

Two other cases are studied in which the slope factor k equals 5 and 10. The reliability data for the bus bars obtained using the accurate and approximate approaches when k equals 5 and 10 are shown in Tables G.1 and G.2 respectively in the Appendix. The unavailabilities obtained using the accurate method are a little smaller than those obtained using the approximate method and the differences are negligible. The failure rate and the repair time are identical using these two methods.

Figure 6.19 shows a comparison of the load point and system EENS for the modified RBTS with ring bus schemes using the approximate method for the three cases with different slope factors.

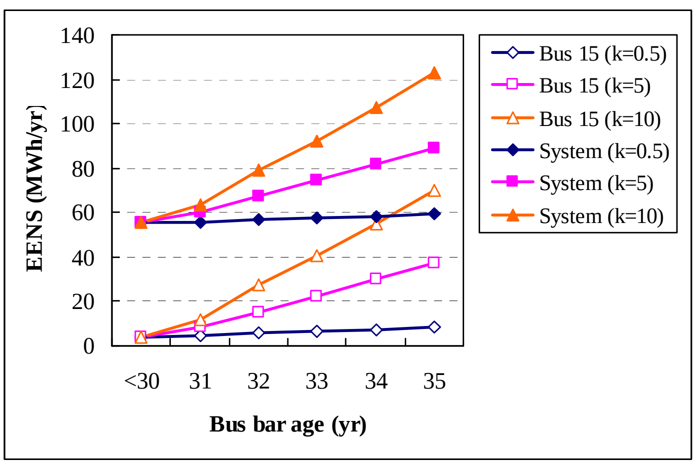

Figure 6.19: Selected load point and system EENS comparison for the three different bus bar slope factors

The result shows that bus bar aging failures have relatively small effects on the RBTS reliability in the first five years after the bus bars enter the wear-out region when the slope factor *k* is small. The aging failure effects of the bus bars on the load point and system EENS, however, increase when the slope factor *k* increases. Bus bar aging failures can have significant impact on the load point and system reliability when the slope factor *k* is relatively large.

6.4.2 Incorporating Circuit Breaker Aging Failures in the Modified RBTS

The effects of circuit breaker aging failures were incorporated in the modified RBTS reliability evaluation and investigated over a relatively long term. The modified RBTS with ring bus schemes is shown in Figure 4.11. The useful life of circuit breakers is assumed to be ten years and the replacement time is assumed to be six days. All the circuit breakers are assumed to be over ten years old.

Table 6.8 shows the reliability data for the circuit breakers including random and aging failures using the accurate and approximate approaches. The slope factor *k* is 0.5 in this case. It can be seen from Table 6.8 that the error in the unavailability obtained using the approximate approach is less than 1%. The approximate approach is therefore used in following reliability analyses.

Table 6.8: Reliability data for the circuit breakers of the modified RBTS in a long term (*k*=0.5)

Circuit breaker age (yr)	Equivalent active failure rate (f/yr)	Equivalent passive failure rate (f/yr)	Equivalent repair time (hr)	Unavailability (hr/yr) (accurate)	Unavailability (hr/yr) (approximate)
<10	0.00963	0.00107	93.62	1.011254	1.001734
10	0.009871	0.001097	94.848780	1.049999	1.040254
20	0.014686	0.001632	110.963934	1.824959	1.810654
30	0.019501	0.002167	119.120988	2.599783	2.581054
40	0.024316	0.002702	124.047525	3.374469	3.351454
50	0.029131	0.003237	127.345455	4.149019	4.121854

Load point and system EENS as a function of the circuit breaker age are shown in Figure 6.20. This figure shows that the load point and system EENS increase slowly with increase in the circuit breaker age when the slope factor *k* is small. Two additional cases are analyzed in which *k* equals 5 and 10.

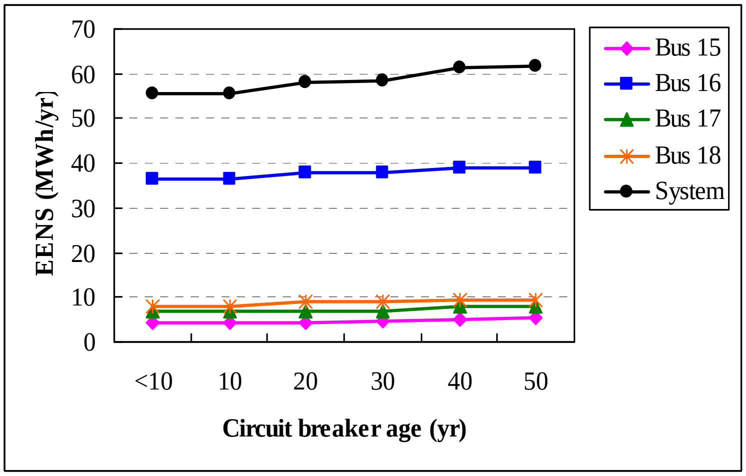

Figure 6.20: Load point and the modified RBTS EENS as a function of the circuit breaker age

The reliability data for the circuit breakers obtained using the accurate and approximate methods when *k* equals 5 and 10 are shown in Tables G.3 and G.4 respectively. The total unavailabilities of the circuit breaker obtained using the accurate method are a little larger than those obtained using the approximate method. The modified circuit breaker reliability data is used to examine the effects of circuit breaker aging failures.

Figures 6.21 and 6.22 respectively show the load point and system EENS as a function of the circuit breaker age when *k* equals 5 and 10. These two figures show that the load point and system EENS increase rapidly with increase in the circuit breaker age. The major contribution to the increase in the system EENS is from the load point at bus16 (Station 3), which carries the heaviest load in the system.

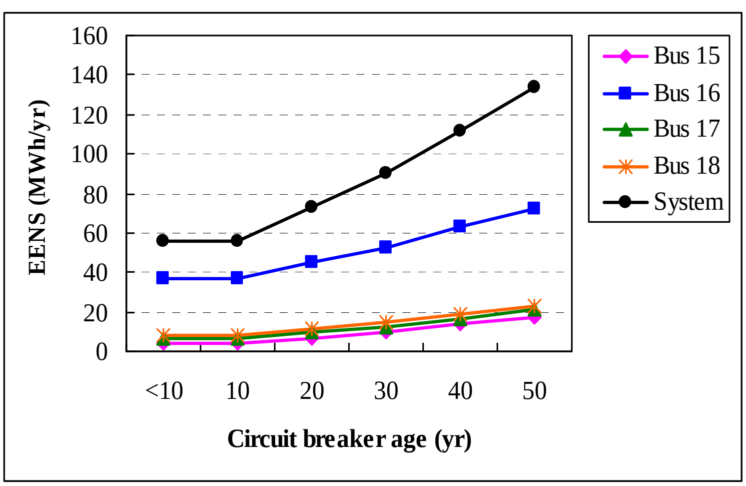

Figure 6.21: Load point and the modified RBTS EENS as a function of the circuit breaker age (k=5)

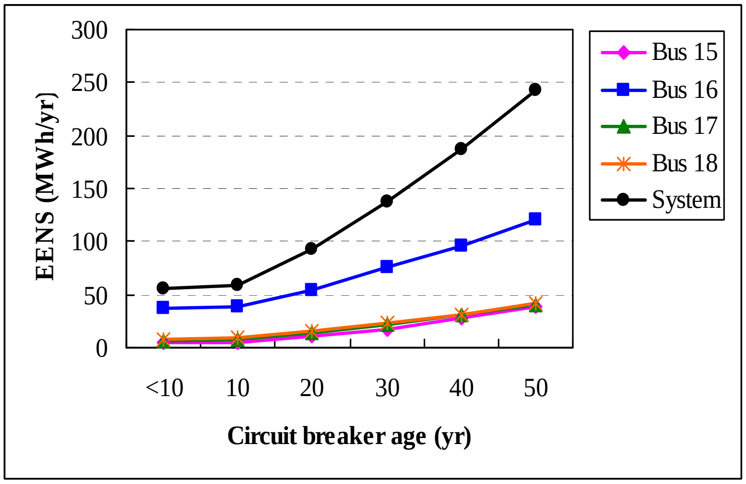

Figure 6.22: Load point and modified RBTS EENS as a function of the circuit breaker age (k=10)

Figure 6.23 shows a comparison of the system EENS for the modified RBTS with the three different slope factors. It can be seen that the load point and system EENS increase rapidly after the circuit breakers enter the wear-out period when the slope factor k is large. Circuit breaker aging failures can have significant impacts on the load point and system reliability in these cases.

Aging failures of circuit breakers are incorporated in the reliability evaluation of the modified RBTS in order to highlight the effect of this condition. The results show that the load point and system EENS increase relatively slowly when the circuit breaker slope factor is small but increase rapidly with increase in the slope factor. The slope factor will increase quickly if adequate preventive maintenance is not performed. Preventive maintenance is a very important function in an electric power system.

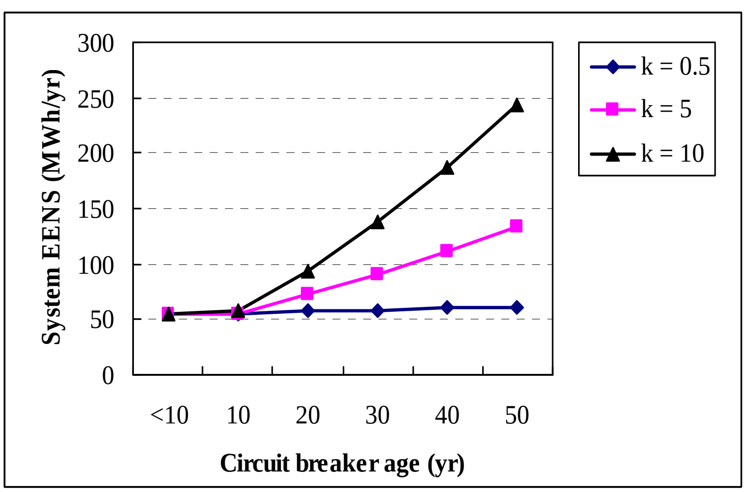

Figure 6.23: Modified RBTS EENS comparison for three different circuit breaker slope factors

6.5 Summary

This chapter presents two different evaluation methods to incorporate station component aging failures in composite system reliability evaluation. Normal and Weibull distribution models are utilized in Method I to evaluate component unavailability due to aging failures. In Method II, station component models together with accurate and approximate evaluation processes are developed to incorporate aging failures in the reliability parameters for bus bars and circuit breakers.

Using Method I, aging failures of generating unit transformers are incorporated in a reliability evaluation of the modified RBTS and the IEEE-RTS using normal and Weibull distribution models. The unavailability due to aging failures using the Weibull distribution model is a little larger than that obtained using the normal distribution model. The load point and system EENS obtained using the Weibull distribution model are higher than those obtained using the normal distribution model, particularly when components are close to their mean life. The results indicate that the effects of generating unit transformer aging failures on the load point and system reliability are comparatively small when the transformers are at an early point in their lives. Aging failure effects, however, become much larger when the transformers reach their mean lives.

Aging failures of transmission transformers are incorporated in an IEEE-RTS reliability evaluation. These aging failure effects are smaller than those of generating unit transformers in this case and illustrates that the IEEE-RTS has adequate transmission and a weak generation system.

In Method II, station component reliability parameters obtained using the accurate and approximate approaches are compared. The analyses show that most of the bus bar and circuit breaker reliability parameters are identical. The unavailability due to bus bar aging failures obtained using the approximate approach is little larger than that obtained using the accurate approach. The unavailability due to circuit breaker aging failures using the approximate approach, however, is little smaller than that obtained using the accurate approach. The approximate evaluation approach is considered to be acceptable and was used in the studies described.

The bus bar and circuit breaker reliability parameters are used as input data to examine the aging effects on the modified RBTS with ring bus schemes. The results show that aging failures of bus bars and circuit breakers can have significant impact on the load point and system reliability of a composite system. The aging effects on the load point and system EENS are relatively small when the component slope factors are small. These effects, however, become much larger as the slope factors increase. The most sensitive load point to circuit breaker aging failures is at Station 3, which has the heaviest load in the system.

The effects on composite system reliability of station component aging failures are dominated by the component slope factors which are affected by the system maintenance policies. Too little maintenance can result in a large slope factor. It is necessary to conduct preventive maintenance on the station components in order to prolong their useful life and to keep their failure rates from increasing. The previous chapters in this thesis show that the removal of equipment for maintenance creates a more vulnerable system and increases the predicted load point and system EENS. The effects on the load point and system indices of circuit breaker maintenance rates, however, are much smaller than those of circuit breaker failure rates. It is a challenge to create an optimal plan for preventive maintenance not only to keep station components in good working condition and to maximize their life but also to minimize the effects of station related maintenance outages.

Chapter 7

Summary and Conclusions

The objective in composite system reliability evaluation is to examine the adequacy of the combined generation and transmission system with respect to the system demand at its terminal stations. Substations and switching stations (stations) are important elements and are energy transfer points between power sources, transmission lines and customers. The reliability of a composite system is a function of the reliability of all the components in the bulk system. The individual station components and the station configurations are important elements in the bulk system. The purpose of this research is to develop models and techniques to incorporate station related outages, including maintenance outages and aging outages in composite system reliability evaluation. The research examines the reliability implications of maintenance and aging failures in the basic station configurations using two practical test systems.

The first chapter provides a brief background on the reliability evaluation of electric power systems and notes that station related maintenance and aging outages are important factors in station reliability. The basic concepts and evaluation techniques utilized in composite systems are briefly described in Chapter 2. Bulk system reliability can be evaluated either by using analytical techniques or by the application of Monte Carlo simulation methods. Monte Carlo simulation can be used to perform assessments including complex operating conditions and is applied in this thesis. Three basic Monte Carlo simulation techniques designated as state sampling, state transition sampling and sequential analysis are introduced. The MECORE program is based on the state sampling approach and is designed to conduct reliability and reliability worth assessments of composite systems. This program has been utilized to conduct all the bulk system reliability studies presented in this thesis.

The reliability of a composite system can be evaluated using the load point and system indices. The load point indices are used to determine the adequacy at the distribution supply points while the system indices provide an overall evaluation of the total system reliability and reliability worth. Both sets of indices can be expressed using annualized or annual values. Annualized indices utilize a constant load level and annual indices incorporate the hourly variations in system load and estimate the actual unsupplied energy and customer damage costs for the system. The annual indices are utilized throughout this thesis.

Two composite test systems known as the RBTS and the IEEE-RTS are used in this research and the annualized and annual indices for the two original systems are given. The original test systems have been extended to include some additional considerations in the form of economic priority order, generating unit transformers, load point transformers and common mode failures. The load point and system reliability indices for the two test systems with generating unit transformers are very close to those for the original systems and are used as base case results. The load point step-down transformers have a significant effect on the load point reliability indices and are not included. The effect on the load point and system reliability of common mode outages is relatively small but is dependent on many factors including the number of multi-circuit tower structures in the system.

Chapter 3 describes the evaluation technique used to incorporate station related forced and maintenance outages in composite system reliability evaluation. The state space models for the individual station components and the relevant equations are presented. The minimal cut set method is used to incorporate the related station equipment failure data in the reliability parameters of the connected terminal components. The evaluation technique is illustrated using a ring bus station. The results show that the connected element failure rate and unavailability due to station related forced outages are larger than those due to station related maintenance outages. The reliability of all the connected terminals decreases slightly after station related maintenance outages are included.

The impact on composite system reliability performance of incorporating station related maintenance outages is illustrated by application to the RBTS and the IEEE-RTS in Chapter 4. The load point and system reliability indices are evaluated and compared for the RBTS and the modified RBTS with ring bus, double bus double breaker, one and one half breaker and one and one third breaker configurations. The reliability indices of the IEEE-RTS with ring bus configurations and with mixed station configurations are analyzed and compared. The load point and system EENS increase at different rates by incorporating station related maintenance outages in the composite system evaluation.

Reliability analyses for the RBTS with the four different station schemes show that double bus double breaker configurations are the most reliable and ring bus configurations are the least reliable. The double bus double breaker configurations, however, are the most expensive and require the most equipment.

The load point and system reliability indices in the original RBTS are dominated by the indices at Station 6 due to the radial line supply to this bus. The system was modified in order to more clearly focus on the effects of station related maintenance outages. Reliability studies show that the modified RBTS with ring bus schemes is the least reliable system. The EENS and SI for the system with double bus double breaker, one and one half breaker and one and one third breaker schemes are very similar in cases where station related maintenance is considered and not included in the analysis. This is not the case when the station component reliability data changes.

Station maintenance outages are incorporated in the reliability evaluation of the IEEE-RTS with ring bus schemes. Six ring stations were selected for modification to one and one half breaker schemes in order to improve the system reliability. The load point EENS at the modified stations decrease significantly for the mixed station schemes compared to those for the ring bus schemes. The predicted composite system reliability performance decreases as station maintenance outages are incorporated.

It is important and necessary to incorporate station related maintenance outages in composite system reliability evaluation. Probabilistic analyses not considering station related maintenance outage underestimate the effects of station related outages on composite system reliability performance. This can lead to improper decisions in the station planning, design and operation process.

The effects of variations in station component reliability parameters on the load point and system reliability of the modified RBTS and IEEE-RTS with different station configurations are presented in Chapter 5. The load point and system EENS for the two composite systems increase as the circuit breaker failure rates, circuit breaker maintenance rates and bus bar failure rates increase while the impacts of their variations are different.

The reliability indices for the modified RBTS with ring bus schemes are more sensitive to variations in the bus bar failure rates than to variations in the circuit breaker failure rates. Double bus double breaker, one and one half breaker and one and one third breaker schemes are more sensitive to variations in the circuit breaker failure rates than to variations in the circuit breaker maintenance rates and bus bar failure rates. The variations in the circuit breaker failure rates have the most significant effect on the reliability performance of the system with one and one third breaker schemes. One and one half breaker schemes are relatively more sensitive to variations in circuit breaker failure rates than double bus double breaker schemes. Station configurations play an important role on the load point and system reliability performance of a composite system.

The analyses performed on the IEEE-RTS are done with ring bus schemes and mixed station schemes. Station component reliability data on the low voltage and high voltage sides are varied separately to examine their effects on the load point and system reliability of the IEEE-RTS with the two different station schemes. The results show the effects on the IEEE-RTS reliability performance of variations in the circuit breaker failure and maintenance rates and bus bar failure rates and provide useful information for decision making in station design, reinforcement and maintenance planning.

Station configurations and topologies can have considerable impact on composite system reliability performance. Failure events within a generating station in addition to a transmission station can affect the load point indices at other stations due to the generation station topology. The effects of station topologies on composite system reliability indices are illustrated by changing a ring bus station to two different ring bus configurations. The results indicate that a proper station design is crucial to obtain optimal reliability performance of a composite power system.

Circuit breaker maintenance rates have relatively small effects on the system indices compared with circuit breaker failure rates. The effects of circuit breaker maintenance rates become larger with increase in the failure rates of circuit breakers or bus bars, particularly when both the circuit breaker and bus bar failure rates increase simultaneously. This implies that the effects of circuit breaker maintenance rates become larger as station components age. The load point and system reliability degrade as station components age and will further degrade as component maintenance frequencies increase. Maintenance is required to maintain electric equipment in good operating condition and prolong the useful life. Preventive maintenance slows down the aging process and helps to keep the failure rate from increasing. Maintenance during the component deterioration process can provide reliability improvements when the effects on the system reliability of the component failure rate are larger than those of the maintenance rate.

Chapter 6 presents two different evaluation methods to incorporate station component aging failures in composite system reliability evaluation. The first method is used to incorporate generating unit transformer aging failures in a reliability evaluation of the modified RBTS and the IEEE-RTS using normal and Weibull distribution models. The load point and system EENS obtained using the Weibull distribution model are higher than those obtained using the normal distribution model, particularly when components are close to their mean life. The effects of generating unit transformer aging failures on the load point and system reliability for the two composite systems are comparatively small when the transformers are at an early point in their lives. These aging failure effects, however, become much larger when the transformers reach their mean lives. Aging failures of transmission transformers are incorporated in an IEEE-RTS reliability evaluation. These aging failure effects are smaller than those of generating unit transformers in this case and illustrates that the IEEE-RTS has adequate transmission and a weak generation system.

Bus bar and circuit breaker aging failures are incorporated in a reliability evaluation of the modified RBTS with ring bus schemes using the second method. Aging failures of bus bars and circuit breakers can have significant impacts on the load point and system reliability of a composite system. The aging effects on the load point and system EENS are relatively small when the component slope factors are small. These effects, however, become much larger as the slope factors increase. This is clearly illustrated in Chapter 6.

The effects on composite system reliability of station component aging failures are dominated by the component slope factors, which are affected by the system maintenance policies. Too little maintenance can result in a large slope factor. It is necessary to conduct preventive maintenance on the station components in order to prolong their useful life and to keep their failure rates from increasing. The removal of equipment for maintenance creates a more vulnerable system and increases the predicted load point and system EENS. The effects on the load point and system indices of circuit breaker maintenance rates, however, are much smaller than those of circuit breaker failure rates. It is a challenge to create an optimal plan for preventive maintenance, not only to keep station components in good working condition and to maximize their life, but also to minimize the effects of station related maintenance outages.

The research presented in this thesis is focused on the development and application of probabilistic techniques to incorporate station related outages including maintenance outages and aging outages in composite system reliability analysis. It is believed that the techniques and conclusions provide valuable information for a wide range of system planning, design, reinforcement and maintenance applications, including design and modification of power stations and station maintenance planning.

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APPENDICES

APPENDIX A. BASIC DATA FOR THE RBTS AND THE IEEE-RTS

Tables A.1-A.3 and A.4-A.6 present the bus, transmission line and generator data for the RBTS and the IEEE-RTS respectively.

Table A.1: Bus data for the RBTS

Bus No.	Load (p.u.)		P_g	Q_{max}	Q_{min}	V_0	V_{max}	V_{min}
	Active	Reactive						
1	0.00	0.0	1.0	0.50	-0.40	1.05	1.05	0.97
2	0.20	0.0	1.2	0.75	-0.40	1.05	1.05	0.97
3	0.85	0.0	0.0	0.00	0.00	1.00	1.05	0.97
4	0.40	0.0	0.0	0.00	0.00	1.00	1.05	0.97
5	0.20	0.0	0.0	0.00	0.00	1.00	1.05	0.97
6	0.20	0.0	0.0	0.00	0.00	1.00	1.05	0.97

Table A.2: Line data for the RBTS

Line	Bus		R	X	B/2	Tap	Current Rating (p.u.)	Failure Rate (occ/yr)	Repair Time (hrs)	Failure Prob.
	I	J								
1,6	1	3	0.0342	0.18	0.0106	1.0	0.85	1.50	10.0	0.00171
2,7	2	4	0.1140	0.60	0.0352	1.0	0.71	5.00	10.0	0.00568
3	1	2	0.0912	0.48	0.0282	1.0	0.71	4.00	10.0	0.00455
4	3	4	0.0228	0.12	0.0071	1.0	0.71	1.00	10.0	0.00114
5	3	5	0.0228	0.12	0.0071	1.0	0.71	1.00	10.0	0.00114
8	4	5	0.0228	0.12	0.0071	1.0	0.71	1.00	10.0	0.00114
9	5	6	0.0228	0.12	0.0071	1.0	0.71	1.00	10.0	0.00114

Table A.3: Generator data for the RBTS

Unit No.	Bus No.	Rating (MW)	Failure Rate (occ/yr)	Repair Time (hrs)	Failure Prob.
1	1	40.0	6.0	45.0	0.03
2	1	40.0	6.0	45.0	0.03
3	1	10.0	4.0	45.0	0.02
4	1	20.0	5.0	45.0	0.025

Table A.3: (Continued)

Unit No.	Bus No.	Rating (MW)	Failure Rate (occ/yr)	Repair Time (hrs)	Failure Prob.
5	2	5.0	2.0	45.0	0.01
6	2	5.0	2.0	45.0	0.01
7	2	40.0	3.0	60.0	0.02
8	2	20.0	2.4	55.0	0.015
9	2	20.0	2.4	55.0	0.015
10	2	20.0	2.4	55.0	0.015
11	2	20.0	2.4	55.0	0.015

Table A.4: Bus data for the IEEE-RTS

Bus No.	Load (p.u.)		P_g	Q_{max}	Q_{min}	V_0	V_{max}	V_{min}
	Active	Reactive						
1	1.08	0.22	1.92	1.20	-0.75	1.00	1.05	0.95
2	0.97	0.20	1.92	1.20	-0.75	1.00	1.05	0.95
3	1.80	0.37	0.00	0.00	0.00	1.00	1.05	0.95
4	0.74	0.15	0.00	0.00	0.00	1.00	1.05	0.95
5	0.71	0.14	0.00	0.00	0.00	1.00	1.05	0.95
6	1.36	0.28	0.00	0.00	0.00	1.00	1.05	0.95
7	1.25	0.25	3.00	2.70	0.00	1.00	1.05	0.95
8	1.71	0.35	0.00	0.00	0.00	1.00	1.05	0.95
9	1.75	0.36	0.00	0.00	0.00	1.00	1.05	0.95
10	1.95	0.40	0.00	0.00	0.00	1.00	1.05	0.95
11	0.00	0.00	0.00	0.00	0.00	1.00	1.05	0.95
12	0.00	0.00	0.00	0.00	0.00	1.00	1.05	0.95
13	2.65	0.54	5.91	3.60	0.00	1.00	1.05	0.95
14	1.94	0.39	0.00	3.00	-0.75	1.00	1.05	0.95
15	3.17	0.64	2.15	1.65	-0.75	1.00	1.05	0.95
16	1.00	0.20	1.55	1.20	-0.75	1.00	1.05	0.95
17	0.00	0.00	0.00	0.00	0.00	1.00	1.05	0.95
18	3.33	0.68	4.00	3.00	-0.75	1.00	1.05	0.95
19	1.81	0.37	0.00	0.00	0.00	1.00	1.05	0.95
20	1.28	0.26	0.00	0.00	0.00	1.00	1.05	0.95
21	0.00	0.00	4.00	3.00	-0.75	1.00	1.05	0.95
22	0.00	0.00	3.00	1.45	-0.90	1.00	1.05	0.95
23	0.00	0.00	6.60	4.50	-0.75	1.00	1.05	0.95
24	0.00	0.00	0.00	0.00	0.00	1.00	1.05	0.95

Table A.5: Line data for the IEEE-RTS

Line No.	Bus I	Bus J	R	X	B/2	Tap	Current Rating (p.u.)	Failure Rate (occ/yr)	Repair Time (hrs)
1	1	2	0.0260	0.0139	0.2306	1.00	1.75	0.240	16.0
2	1	3	0.0546	0.2112	0.0286	1.00	1.75	0.510	10.0
3	1	5	0.0218	0.0845	0.0115	1.00	1.75	0.330	10.0
4	2	4	0.0328	0.1267	0.0172	1.00	1.75	0.390	10.0
5	2	6	0.0497	0.1920	0.0260	1.00	1.75	0.480	10.0
6	3	9	0.0308	0.1190	0.0161	1.00	1.75	0.380	10.0
7	3	24	0.0023	0.0839	0.0000	1.00	4.00	0.020	768.0
8	4	9	0.0268	0.1037	0.0141	1.00	1.75	0.360	10.0
9	5	10	0.0228	0.0883	0.0120	1.00	1.75	0.340	10.0
10	6	10	0.0139	0.0605	1.2295	1.00	1.75	0.330	35.0
11	7	8	0.0159	0.0614	0.0166	1.00	1.75	0.300	10.0
12	8	9	0.0427	0.1651	0.0224	1.00	1.75	0.440	10.0
13	8	10	0.0427	0.1651	0.0224	1.00	1.75	0.440	10.0
14	9	11	0.0023	0.0839	0.0000	1.00	4.00	0.020	768.0
15	9	12	0.0023	0.0839	0.0000	1.00	4.00	0.020	768.0
16	10	11	0.0023	0.0839	0.0000	1.00	4.00	0.020	768.0
17	10	12	0.0023	0.0839	0.0000	1.00	4.00	0.020	768.0
18	11	13	0.0061	0.0476	0.0500	1.00	5.00	0.400	11.0
19	11	14	0.0054	0.0418	0.0440	1.00	5.00	0.390	11.0
20	12	13	0.0061	0.0476	0.0500	1.00	5.00	0.400	11.0
21	12	23	0.0124	0.0966	0.1015	1.00	5.00	0.520	11.0
22	13	23	0.0111	0.0865	0.0909	1.00	5.00	0.490	11.0
23	14	16	0.0050	0.0389	0.0409	1.00	5.00	0.380	11.0
24	15	16	0.0022	0.0173	0.0364	1.00	5.00	0.330	11.0
25	15	21	0.0063	0.0490	0.0515	1.00	5.00	0.410	11.0
26	15	21	0.0063	0.0490	0.0515	1.00	5.00	0.410	11.0
27	15	24	0.0067	0.0519	0.0546	1.00	5.00	0.410	11.0
28	16	17	0.0033	0.0259	0.0273	1.00	5.00	0.350	11.0
29	16	19	0.0030	0.0231	0.0243	1.00	5.00	0.340	11.0
30	17	18	0.0018	0.0144	0.0152	1.00	5.00	0.320	11.0
31	17	22	0.0135	0.1053	0.1106	1.00	5.00	0.540	11.0
32	18	21	0.0033	0.0259	0.0273	1.00	5.00	0.350	11.0
33	18	21	0.0033	0.0259	0.0273	1.00	5.00	0.350	11.0
34	19	20	0.0051	0.0396	0.0417	1.00	5.00	0.380	11.0
35	19	20	0.0051	0.0396	0.0417	1.00	5.00	0.380	11.0
36	20	23	0.0028	0.0216	0.0228	1.00	5.00	0.340	11.0
37	20	23	0.0028	0.0216	0.0228	1.00	5.00	0.340	11.0
38	21	22	0.0087	0.0678	0.0712	1.00	5.00	0.450	11.0

Table A.6: Generator data for the IEEE-RTS

Unit No.	Bus No.	Rating (MW)	Failure Rate (occ/yr)	Repair Time (hrs)	Failure Prob.
1	22	50	4.42	20	0.01
2	22	50	4.42	20	0.01
3	22	50	4.42	20	0.01
4	22	50	4.42	20	0.01
5	22	50	4.42	20	0.01
6	22	50	4.42	20	0.01
7	15	12	2.98	60	0.02
8	15	12	2.98	60	0.02
9	15	12	2.98	60	0.02
10	15	12	2.98	60	0.02
11	15	12	2.98	60	0.02
12	15	155	9.13	40	0.04
13	7	100	7.30	50	0.04
14	7	100	7.30	50	0.04
15	7	100	7.30	50	0.04
16	13	197	9.22	50	0.05
17	13	197	9.22	50	0.05
18	13	197	9.22	50	0.05
19	1	20	19.47	50	0.10
20	1	20	19.47	50	0.10
21	1	76	4.47	40	0.02
22	1	76	4.47	40	0.02
23	2	20	9.13	50	0.10
24	2	20	9.13	50	0.10
25	2	76	4.47	40	0.02
26	2	76	4.47	40	0.02
27	23	155	9.13	40	0.04
28	23	155	9.13	40	0.04
29	23	350	7.62	100	0.08
30	18	400	7.96	150	0.12
31	21	400	7.96	150	0.12
32	16	155	9.13	40	0.04

Tables A.7-A.9 give the per-unit load model for both the RBTS and IEEE-RTS.

Table A.7: The weekly peak load as a percent of annual peak

Week	Peak load	Week	Peak load	Week	Peak load	Week	Peak load
1	86.2	14	75.0	27	75.5	40	72.4
2	90.0	15	72.1	28	81.6	41	74.3
3	87.8	16	80.0	29	80.1	42	74.4

Table A.7: (Continued)

Week	Peak load	Week	Peak load	Week	Peak load	Week	Peak load
4	83.4	17	75.4	30	88.0	43	80.0
5	88.0	18	83.7	31	72.2	44	88.1
6	84.1	19	87.0	32	77.6	45	88.5
7	83.2	20	88.0	33	80.0	46	90.9
8	80.6	21	85.6	34	72.9	47	94.0
9	74.0	22	81.1	35	72.6	48	89.0
10	73.7	23	90.0	36	70.5	49	94.2
11	71.5	24	88.7	37	78.0	50	97.0
12	72.7	25	89.6	38	69.5	51	100.0
13	70.4	26	86.1	39	72.4	52	95.2

Table A.8: Daily peak load as a percentage of weekly load

Day	Peak Load
Monday	93
Tuesday	100
Wednesday	98
Thursday	96
Friday	94
Saturday	77
Sunday	75

Table A.9: Hourly peak load as a percentage of daily peak

Hour	Winter Weeks 1-8&44-52		Summer Weeks 18-30		Spring/Fall Weeks 9-17&31-43	
	Wkdy	Wknd	Wkdy	Wknd	Wkdy	Wknd
12-1am	67	78	64	74	63	75
1-2	63	72	60	70	62	73
2-3	60	68	58	66	60	69
3-4	59	66	56	65	58	66
4-5	59	64	56	64	59	65
5-6	60	65	58	62	65	65
6-7	74	66	64	62	72	68
7-8	86	70	76	66	85	74
8-9	95	80	87	81	95	83
9-10	96	88	95	86	99	89
10-11	96	90	99	91	100	92
11-noon	95	91	100	93	99	94
Noon-1pm	95	90	99	93	93	91
1-2	95	88	100	92	92	90
2-3	93	87	100	91	90	90
3-4	94	87	97	91	88	86
4-5	99	91	96	92	90	85

Table A.9: (Continued)

Hour	Winter Weeks 1-8&44-52		Summer Weeks 18-30		Spring/Fall Weeks 9-17&31-43	
	Wkdy	Wknd	Wkdy	Wknd	Wkdy	Wknd
5-6	100	100	96	94	92	88
6-7	100	99	93	95	96	92
7-8	96	97	92	95	98	100
8-9	91	94	92	100	96	97
9-10	83	92	93	93	90	95
10-11	73	87	87	88	80	90
11-12	63	81	72	80	70	85

Note: Wkdy-Weekday, Wknd-Weekend.

MODIFIED DATA FOR THE RBTS AND THE IEEE-RTS

Table A.10 presents the modified generator data for the RBTS with generating unit transformers. The modified generator data for the IEEE-RTS with generating unit transformers are presented in Table A.11.

Table A.10: Modified generator data for the RBTS with generating unit transformers

Unit No.	Bus No.	Capacity (MW)	MTTR (hrs)	Failure Prob.
1	7	40.0	41.38	0.02825
2	8	40.0	41.38	0.02825
3	9	10.0	40.17	0.01825
4	10	20.0	40.90	0.02325
5	11	5.0	36.50	0.00825
6	12	5.0	36.50	0.00825
7	13	40.0	53.65	0.01825
8	14	20.0	48.77	0.01325
9	14	20.0	48.77	0.01325
10	15	20.0	48.77	0.01325
11	15	20.0	48.77	0.01325

Table A.11: Modified generator data for IEEE-RTS with generating unit transformers

Bus No.	Rating (MW)	Failure Rate (occ/yr)	Repair Time (hrs)	Failure Prob.	Modified repair time (hrs)	Modified unavailability
1	20	19.47	50	0.1	43.57838	0.09674
1	20	19.47	50	0.1	43.57838	0.09674
1	76	4.47	40	0.02	32.96054	0.01674
1	76	4.47	40	0.02	32.96054	0.01674
2	20	19.47	50	0.1	43.57838	0.09674
2	20	19.47	50	0.1	43.57838	0.09674

Table A.11: (Continued)

Bus No.	Rating (MW)	Failure Rate (occ/yr)	Repair Time (hrs)	Failure Prob.	Modified repair time (hrs)	Modified unavailability
2	76	4.47	40	0.02	32.96054	0.01674
2	76	4.47	40	0.02	32.96054	0.01674
7	100	7.30	50	0.04	44.21075	0.03674
7	100	7.30	50	0.04	44.21075	0.03674
7	100	7.30	50	0.04	44.21075	0.03674
13	197	9.22	50	0.05	45.38442	0.04767
13	197	9.22	50	0.05	45.38442	0.04767
13	197	9.22	50	0.05	45.38442	0.04767
15	12	2.98	60	0.02	52.29924	0.01767
15	12	2.98	60	0.02	52.29924	0.01767
15	12	2.98	60	0.02	52.29924	0.01767
15	12	2.98	60	0.02	52.29924	0.01767
15	12	2.98	60	0.02	52.29924	0.01767
15	155	9.13	40	0.04	36.24211	0.03767
16	155	9.13	40	0.04	36.24211	0.03767
18	400	7.96	150	0.12	129.76228	0.11767
21	400	7.96	150	0.12	129.76228	0.11767
22	50	4.42	20	0.01	15.25447	0.00767
22	50	4.42	20	0.01	15.25447	0.00767
22	50	4.42	20	0.01	15.25447	0.00767
22	50	4.42	20	0.01	15.25447	0.00767
22	50	4.42	20	0.01	15.25447	0.00767
22	50	4.42	20	0.01	15.25447	0.00767
23	155	9.13	40	0.04	36.24211	0.03767
23	155	9.13	40	0.04	36.24211	0.03767
23	350	7.62	100	0.08	89.55500	0.07767

APPENDIX B. MODIFIED DATA FOR THE RBTS WITH FOUR DIFFERENT STATION CONFIGURATIONS

The modified generator data for the RBTS with four different station configurations are the same as table A.10. Tables B.1 to B.4 present the modified line, transformer and equivalent load circuit for the RBTS with four different station schemes respectively, without considering station related maintenance outages. Tables B.5 to B.8 present the modified line and transformer data for the RBTS with four different station schemes respectively, considering station related maintenance outages.

WITHOUT STATION RELATED MAINTENANCE OUTAGES

Table B.1: Modified line and transformer data for the RBTS with ring bus schemes (without station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1,6	1	3	5.55556	0.85	10.00003	0.001769
2,7	2	4	1.66667	0.71	10.00001	0.005765
3	1	2	2.08333	0.71	10.00002	0.004623
4	3	4	8.33333	0.71	10.00002	0.001199
5	3	5	8.33333	0.71	10.00005	0.001199
8	4	5	8.33333	0.71	10.00005	0.001199
9	5	6	8.33333	0.71	10.00002	0.001170
10	1	7	11.91900	0.48	346.77539	0.001782
11	1	8	11.91900	0.48	346.77539	0.001782
12	1	9	11.91900	0.12	346.77539	0.001782
13	1	10	11.91900	0.24	346.77539	0.001782
14	2	11	11.91900	0.06	346.77539	0.001782
15	2	12	11.91900	0.06	346.77539	0.001782
16	2	13	11.91900	0.48	346.77539	0.001782
17	2	14	11.91900	0.48	346.77539	0.001782
18	2	15	11.91900	0.48	346.77539	0.001782
19	2	16	11.91900	0.24	10.00205	0.000029
20	3	17	11.91900	1.02	10.00034	0.000029
21	4	18	11.91900	0.48	10.00034	0.000029
22	5	19	11.91900	0.24	10.00073	0.000029
23	6	20	11.91900	0.24	7.49865	0.000059

Table B.2: Modified line and transformer data for the RBTS with double bus double breaker schemes (without station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1,6	1	3	5.55556	0.85	9.77470	0.001717
2,7	2	4	1.66667	0.71	9.93120	0.005712
3	1	2	2.08333	0.71	9.91413	0.004571
4	3	4	8.33333	0.71	9.66635	0.001146
5	3	5	8.33333	0.71	9.66635	0.001146
8	4	5	8.33333	0.71	9.66635	0.001146
9	5	6	8.33333	0.71	9.83002	0.001144
10	1	7	11.91900	0.48	391.51249	0.001756
11	1	8	11.91900	0.48	391.51249	0.001756
12	1	9	11.91900	0.12	391.51249	0.001756
13	1	10	11.91900	0.24	391.51249	0.001756
14	2	11	11.91900	0.06	391.46823	0.001756
15	2	12	11.91900	0.06	391.46823	0.001756
16	2	13	11.91900	0.48	391.46823	0.001756
17	2	14	11.91900	0.48	391.46823	0.001756
18	2	15	11.91900	0.48	391.46823	0.001756
19	2	16	11.91900	0.24	1.00844	0.000002
20	3	17	11.91900	1.02	1.00846	0.000002
21	4	18	11.91900	0.48	1.00846	0.000002
22	5	19	11.91900	0.24	1.00846	0.000002
23	6	20	11.91900	0.24	1.01442	0.000004

Table B.3: Modified line and transformer data for the RBTS with one and half breaker schemes (without station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1	1	3	5.55556	0.85	9.83003	0.001716
6	1	3	5.55556	0.85	9.88595	0.001715
2	2	4	1.66667	0.71	9.94832	0.005711
7	2	4	1.66667	0.71	9.96547	0.005710
3	1	2	2.08333	0.71	9.95689	0.004568
4	3	4	8.33333	0.71	9.82996	0.001144
5	3	5	8.33333	0.71	9.83006	0.001144
8	4	5	8.33333	0.71	9.83006	0.001144
9	5	6	8.33333	0.71	9.91429	0.001143
10	1	7	11.91900	0.48	518.49269	0.001755
11	1	8	11.91900	0.48	518.49269	0.001755
12	1	9	11.91900	0.12	518.49269	0.001755

Table B.3: (Continued)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
13	1	10	11.91900	0.24	391.47537	0.001756
14	2	11	11.91900	0.06	518.47326	0.001755
15	2	12	11.91900	0.06	391.43617	0.001756
16	2	13	11.91900	0.48	518.47326	0.001755
17	2	14	11.91900	0.48	518.47326	0.001755
18	2	15	11.91900	0.48	518.47326	0.001755
19	2	16	11.91900	0.24	1.01426	0.000001
20	3	17	11.91900	1.02	1.01424	0.000001
21	4	18	11.91900	0.48	1.01424	0.000001
22	5	19	11.91900	0.24	1.02586	0.000001
23	6	20	11.91900	0.24	34.07857	0.000117

Table B.4: Modified line and transformer data for the RBTS with one and one third breaker schemes (without station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1	1	3	5.55556	0.85	9.83010	0.001716
6	1	3	5.55556	0.85	10.00007	0.001712
2	2	4	1.66667	0.71	9.96550	0.005710
7	2	4	1.66667	0.71	9.96554	0.005710
3	1	2	2.08333	0.71	9.93551	0.004570
4	3	4	8.33333	0.71	9.83028	0.001144
5	3	5	8.33333	0.71	9.74773	0.001145
8	4	5	8.33333	0.71	9.74773	0.001145
9	5	6	8.33333	0.71	9.83024	0.001144
10	1	7	11.91900	0.48	518.52268	0.001755
11	1	8	11.91900	0.48	518.52268	0.001755
12	1	9	11.91900	0.12	391.56547	0.001756
13	1	10	11.91900	0.24	391.56547	0.001756
14	2	11	11.91900	0.06	518.56155	0.001755
15	2	12	11.91900	0.06	518.56155	0.001755
16	2	13	11.91900	0.48	518.56155	0.001755
17	2	14	11.91900	0.48	767.65581	0.001753
18	2	15	11.91900	0.48	518.56155	0.001755
19	2	16	11.91900	0.24	20.47732	0.000000
20	3	17	11.91900	1.02	1.02589	0.000002
21	4	18	11.91900	0.48	1.02589	0.000002
22	5	19	11.91900	0.24	1.02589	0.000002
23	6	20	11.91900	0.24	49.74737	0.000231

CONSIDERING STATION RELATED MAINTENANCE OUTAGES

Table B.5: Modified line and transformer data for the RBTS with ring bus schemes (considering station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1	1	3	5.55556	0.85	10.00124	0.001770
6	1	3	5.55556	0.85	10.00124	0.001770
2	2	4	1.66667	0.71	10.00038	0.005766
7	2	4	1.66667	0.71	10.00038	0.005766
3	1	2	2.08333	0.71	10.00059	0.004624
4	3	4	8.33333	0.71	10.00141	0.001200
5	3	5	8.33333	0.71	10.00226	0.001200
8	4	5	8.33333	0.71	10.00226	0.001200
9	5	6	8.33333	0.71	10.00073	0.001171
10	1	7	11.91900	0.48	122.03353	0.003417
11	1	8	11.91900	0.48	122.03353	0.003417
12	1	9	11.91900	0.12	122.03353	0.003417
13	1	10	11.91900	0.24	122.03353	0.003417
14	2	11	11.91900	0.06	122.03353	0.003417
15	2	12	11.91900	0.06	122.03353	0.003417
16	2	13	11.91900	0.48	122.03353	0.003417
17	2	14	11.91900	0.48	122.03353	0.003417
18	2	15	11.91900	0.48	122.03353	0.003417
19	2	16	11.91900	0.24	10.06489	0.000029
20	3	17	11.91900	1.02	10.02916	0.000029
21	4	18	11.91900	0.48	10.02916	0.000029
22	5	19	11.91900	0.24	10.02956	0.000029
23	6	20	11.91900	0.24	7.53111	0.000060

Table B.6: Modified line and transformer data for the RBTS with double bus double breaker schemes (considering station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1	1	3	5.55556	0.85	9.77466	0.001718
6	1	3	5.55556	0.85	9.77466	0.0017187
2	2	4	1.66667	0.71	9.93099	0.005713
7	2	4	1.66667	0.71	9.93099	0.005713
3	1	2	2.08333	0.71	9.91367	0.004572
4	3	4	8.33333	0.71	9.66716	0.001147
5	3	5	8.33333	0.71	9.66756	0.001147
8	4	5	8.33333	0.71	9.66756	0.001147
9	5	6	8.33333	0.71	9.83079	0.001144
10	1	7	11.91900	0.48	123.89344	0.003391

Table B.6: (Continued)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
11	1	8	11.91900	0.48	123.89344	0.003391
12	1	9	11.91900	0.12	123.89344	0.003391
13	1	10	11.91900	0.24	123.89344	0.003391
14	2	11	11.91900	0.06	123.84249	0.003391
15	2	12	11.91900	0.06	123.84249	0.003391
16	2	13	11.91900	0.48	123.84249	0.003391
17	2	14	11.91900	0.48	123.84249	0.003391
18	2	15	11.91900	0.48	123.84249	0.003391
19	2	16	11.91900	0.24	1.18938	0.000003
20	3	17	11.91900	1.02	1.19148	0.000003
21	4	18	11.91900	0.48	1.19148	0.000003
22	5	19	11.91900	0.24	1.19197	0.000003
23	6	20	11.91900	0.24	1.33178	0.000006

Table B.7: Modified line and transformer data for the RBTS with one and half breaker schemes (considering station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1	1	3	5.55556	0.85	9.83272	0.001717
6	1	3	5.55556	0.85	9.88715	0.001715
2	2	4	1.66667	0.71	9.94900	0.005712
7	2	4	1.66667	0.71	9.96570	0.005711
3	1	2	2.08333	0.71	9.95733	0.004569
4	3	4	8.33333	0.71	9.83117	0.001145
5	3	5	8.33333	0.71	9.83356	0.001145
8	4	5	8.33333	0.71	9.83356	0.001145
9	5	6	8.33333	0.71	9.91760	0.001143
10	1	7	11.91900	0.48	129.15277	0.003390
11	1	8	11.91900	0.48	129.15277	0.003390
12	1	9	11.91900	0.12	129.15277	0.003390
13	1	10	11.91900	0.24	123.88271	0.003391
14	2	11	11.91900	0.06	129.13891	0.003390
15	2	12	11.91900	0.06	123.84419	0.003391
16	2	13	11.91900	0.48	129.13891	0.003390
17	2	14	11.91900	0.48	129.13891	0.003390
18	2	15	11.91900	0.48	129.13891	0.003390
19	2	16	11.91900	0.24	1.32734	0.000001
20	3	17	11.91900	1.02	1.32563	0.000002
21	4	18	11.91900	0.48	1.32563	0.000002
22	5	19	11.91900	0.24	1.59643	0.000002
23	6	20	11.91900	0.24	34.07857	0.000117

Table B.8: Modified line and transformer data for the RBTS with one and one third breaker schemes (considering station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1	1	3	5.55556	0.85	9.83421	0.001717
6	1	3	5.55556	0.85	10.00175	0.001713
2	2	4	1.66667	0.71	9.96641	0.005711
7	2	4	1.66667	0.71	9.96738	0.005712
3	1	2	2.08333	0.71	9.93663	0.004571
4	3	4	8.33333	0.71	9.83857	0.001145
5	3	5	8.33333	0.71	9.75822	0.001147
8	4	5	8.33333	0.71	9.75822	0.001147
9	5	6	8.33333	0.71	9.83768	0.001145
10	1	7	11.91900	0.48	129.16697	0.003390
11	1	8	11.91900	0.48	129.16697	0.003390
12	1	9	11.91900	0.12	123.96551	0.003391
13	1	10	11.91900	0.24	123.96551	0.003391
14	2	11	11.91900	0.06	129.19469	0.003390
15	2	12	11.91900	0.06	129.19469	0.003390
16	2	13	11.91900	0.48	129.19469	0.003390
17	2	14	11.91900	0.48	134.79301	0.003388
18	2	15	11.91900	0.48	129.19469	0.003390
19	2	16	11.91900	0.24	22.59532	0.000001
20	3	17	11.91900	1.02	1.60259	0.000004
21	4	18	11.91900	0.48	1.60259	0.000004
22	5	19	11.91900	0.24	1.60259	0.000004
23	6	20	11.91900	0.24	49.74737	0.000231

APPENDIX C. MODIFIED DATA FOR THE MODIFIED RBTS WITH FOUR DIFFERENT STATION CONFIGURATIONS

Tables C.1 to C.4 present the modified line, transformer and generator data for the modified RBTS with four different station schemes respectively, without considering station related maintenance outages. Tables C.5 to C.8 present the modified line, transformer and generator data for the modified RBTS with four different station schemes respectively, considering station related maintenance outages.

WITHOUT STATION RELATED MAINTENANCE OUTAGES

Table C.1: Modified line and transformer data for the modified RBTS with ring bus schemes (without station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1,6	1	3	5.55556	0.85	10.00003	0.001769
2,7	2	4	1.66667	0.71	10.00001	0.005765
3	1	2	2.08333	0.71	10.00002	0.004623
4	3	4	8.33333	0.71	10.00002	0.001199
5	3	5	8.33333	0.71	10.00006	0.001199
8	4	5	8.33333	0.71	10.00006	0.001199
9	1	6	11.91900	0.48	346.77539	0.001782
10	1	7	11.91900	0.48	346.77539	0.001782
11	1	8	11.91900	0.12	346.77539	0.001782
12	1	9	11.91900	0.24	346.77539	0.001782
13	2	10	11.91900	0.06	346.77539	0.001782
14	2	11	11.91900	0.06	346.77539	0.001782
15	2	12	11.91900	0.48	346.77539	0.001782
16	2	13	11.91900	0.48	346.77539	0.001782
17	2	14	11.91900	0.48	346.77539	0.001782
18	2	15	11.91900	0.24	10.00205	0.000029
19	3	16	11.91900	1.02	10.00034	0.000029
20	4	17	11.91900	0.48	10.00034	0.000029
21	5	18	11.91900	0.24	10.00073	0.000029

Table C.2: Modified line and transformer data for the modified RBTS with double bus double breaker schemes (without station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1,6	1	3	5.55556	0.85	9.77470	0.001717
2,7	2	4	1.66667	0.71	9.93120	0.005712
3	1	2	2.08333	0.71	9.91413	0.004571
4	3	4	8.33333	0.71	9.66635	0.001146
5	3	5	8.33333	0.71	9.66635	0.001146
8	4	5	8.33333	0.71	9.66635	0.001146
9	1	6	11.91900	0.48	391.51249	0.001756
10	1	7	11.91900	0.48	391.51249	0.001756
11	1	8	11.91900	0.12	391.51249	0.001756
12	1	9	11.91900	0.24	391.51249	0.001756
13	2	10	11.91900	0.06	391.46823	0.001756
14	2	11	11.91900	0.06	391.46823	0.001756
15	2	12	11.91900	0.48	391.46823	0.001756
16	2	13	11.91900	0.48	391.46823	0.001756
17	2	14	11.91900	0.48	391.46823	0.001756
18	2	15	11.91900	0.24	1.00844	0.000002
19	3	16	11.91900	1.02	1.00846	0.000002
20	4	17	11.91900	0.48	1.00846	0.000002
21	5	18	11.91900	0.24	1.00846	0.000002

Table C.3: Modified line and transformer data for the modified RBTS with one and half breaker schemes (without station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1	1	3	5.55556	0.85	9.83003	0.001716
6	1	3	5.55556	0.85	9.88595	0.001715
2	2	4	1.66667	0.71	9.94832	0.005711
7	2	4	1.66667	0.71	9.96547	0.005710
3	1	2	2.08333	0.71	9.95689	0.004568
4	3	4	8.33333	0.71	9.82996	0.001144
5	3	5	8.33333	0.71	9.74769	0.001145
8	4	5	8.33333	0.71	9.83006	0.001144
9	1	6	11.91900	0.48	518.49269	0.001755
10	1	7	11.91900	0.48	518.49269	0.001755
11	1	8	11.91900	0.12	518.49269	0.001755
12	1	9	11.91900	0.24	391.47537	0.001756
13	2	10	11.91900	0.06	518.47326	0.001755

Table C.3: (Continued)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
14	2	11	11.91900	0.06	391.43617	0.001756
15	2	12	11.91900	0.48	518.47326	0.001755
16	2	13	11.91900	0.48	518.47326	0.001755
17	2	14	11.91900	0.48	518.47326	0.001755
18	2	15	11.91900	0.24	1.01426	0.000001
19	3	16	11.91900	1.02	1.01424	0.000001
20	4	17	11.91900	0.48	1.01424	0.000001
21	5	18	11.91900	0.24	1.03746	0.000001

Table C.4: Modified line and transformer data for the modified RBTS with one and one third breaker schemes (without station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1	1	3	5.55556	0.85	9.83010	0.001716
6	1	3	5.55556	0.85	10.00007	0.001712
2	2	4	1.66667	0.71	9.96550	0.005710
7	2	4	1.66667	0.71	9.96554	0.005710
3	1	2	2.08333	0.71	9.93551	0.004570
4	3	4	8.33333	0.71	9.83028	0.001144
5	3	5	8.33333	0.71	9.74773	0.001145
8	4	5	8.33333	0.71	9.74773	0.001145
9	1	6	11.91900	0.48	518.52268	0.001755
10	1	7	11.91900	0.48	518.52268	0.001755
11	1	8	11.91900	0.12	391.56547	0.001756
12	1	9	11.91900	0.24	391.56547	0.001756
13	2	10	11.91900	0.06	518.56155	0.001755
14	2	11	11.91900	0.06	518.56155	0.001755
15	2	12	11.91900	0.48	518.56155	0.001755
16	2	13	11.91900	0.48	767.65581	0.001753
17	2	14	11.91900	0.48	518.56155	0.001755
18	2	15	11.91900	0.24	20.47732	0.000000
19	3	16	11.91900	1.02	1.02589	0.000002
20	4	17	11.91900	0.48	1.02589	0.000002
21	5	18	11.91900	0.24	1.02589	0.000002

CONSIDERING STATION RELATED MAINTENANCE OUTAGES

Table C.5: Modified line and transformer data for the modified RBTS with ring bus schemes (considering station maintenance outages)

Line	Bus I	Bus J	1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
1	1	3	5.55556	0.85	10.00124	0.001770
6	1	3	5.55556	0.85	10.00124	0.001770
2	2	4	1.66667	0.71	10.00038	0.005766
7	2	4	1.66667	0.71	10.00038	0.005766
3	1	2	2.08333	0.71	10.00059	0.004624
4	3	4	8.33333	0.71	10.00141	0.001200
5	3	5	8.33333	0.71	10.00227	0.001200
8	4	5	8.33333	0.71	10.00227	0.001200
9	1	6	11.91900	0.48	122.03353	0.003417
10	1	7	11.91900	0.48	122.03353	0.003417
11	1	8	11.91900	0.12	122.03353	0.003417
12	1	9	11.91900	0.24	122.03353	0.003417
13	2	10	11.91900	0.06	122.03353	0.003417
14	2	11	11.91900	0.06	122.03353	0.003417
15	2	12	11.91900	0.48	122.03353	0.003417
16	2	13	11.91900	0.48	122.03353	0.003417
17	2	14	11.91900	0.48	122.03353	0.003417
18	2	15	11.91900	0.24	10.06489	0.000029
19	3	16	11.91900	1.02	10.02916	0.000029
20	4	17	11.91900	0.48	10.02916	0.000029
21	5	18	11.91900	0.24	10.02956	0.000029

Table C.6: Modified line and transformer data for the modified RBTS with double bus double breaker schemes (considering station maintenance outages)

Line	Bus I	Bus J	1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
1	1	3	5.55556	0.85	9.77466	0.001718
6	1	3	5.55556	0.85	9.77466	0.001718
2	2	4	1.66667	0.71	9.93099	0.005713
7	2	4	1.66667	0.71	9.93099	0.005713
3	1	2	2.08333	0.71	9.91367	0.004572
4	3	4	8.33333	0.71	9.66716	0.001147
5	3	5	8.33333	0.71	9.66756	0.001147
8	4	5	8.33333	0.71	9.66756	0.001147
9	1	6	11.91900	0.48	123.89344	0.003391
10	1	7	11.91900	0.48	123.89344	0.003391

Table C.6: (Continued)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
11	1	8	11.91900	0.12	123.89344	0.003391
12	1	9	11.91900	0.24	123.89344	0.003391
13	2	10	11.91900	0.06	123.84249	0.003391
14	2	11	11.91900	0.06	123.84249	0.003391
15	2	12	11.91900	0.48	123.84249	0.003391
16	2	13	11.91900	0.48	123.84249	0.003391
17	2	14	11.91900	0.48	123.84249	0.003391
18	2	15	11.91900	0.24	1.18938	0.000003
19	3	16	11.91900	1.02	1.19148	0.000003
20	4	17	11.91900	0.48	1.19148	0.000003
21	5	18	11.91900	0.24	1.19197	0.000003

Table C.7: Modified line and transformer data for the modified RBTS with one and half breaker schemes (considering station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1	1	3	5.55556	0.85	9.83272	0.001717
6	1	3	5.55556	0.85	9.88715	0.001715
2	2	4	1.66667	0.71	9.94900	0.005712
7	2	4	1.66667	0.71	9.96570	0.005711
3	1	2	2.08333	0.71	9.95733	0.004569
4	3	4	8.33333	0.71	9.83117	0.001145
5	3	5	8.33333	0.71	9.75767	0.001147
8	4	5	8.33333	0.71	9.83356	0.001145
9	1	6	11.91900	0.48	129.15277	0.003390
10	1	7	11.91900	0.48	129.15277	0.003390
11	1	8	11.91900	0.12	129.15277	0.003390
12	1	9	11.91900	0.24	123.88271	0.003391
13	2	10	11.91900	0.06	129.13891	0.003390
14	2	11	11.91900	0.06	123.84419	0.003391
15	2	12	11.91900	0.48	129.13891	0.003390
16	2	13	11.91900	0.48	129.13891	0.003390
17	2	14	11.91900	0.48	129.13891	0.003390
18	2	15	11.91900	0.24	1.32734	0.000001
19	3	16	11.91900	1.02	1.32563	0.000002
20	4	17	11.91900	0.48	1.32563	0.000002
21	5	18	11.91900	0.24	1.85695	0.000002

Table C.8: Modified line and transformer data for the modified RBTS with one and one third breaker schemes (considering station maintenance outages)

Line	Bus		1/Reactance	Current Rating (p.u.)	MTTR (hrs)	Failure Prob.
	I	J				
1	1	3	5.55556	0.85	9.83421	0.001717
6	1	3	5.55556	0.85	10.00175	0.001713
2	2	4	1.66667	0.71	9.96641	0.005711
7	2	4	1.66667	0.71	9.96738	0.005712
3	1	2	2.08333	0.71	9.93663	0.004571
4	3	4	8.33333	0.71	9.83857	0.001145
5	3	5	8.33333	0.71	9.75822	0.001147
8	4	5	8.33333	0.71	9.75822	0.001147
9	1	6	11.91900	0.48	129.16697	0.003390
10	1	7	11.91900	0.48	129.16697	0.003390
11	1	8	11.91900	0.12	123.96551	0.003391
12	1	9	11.91900	0.24	123.96551	0.003391
13	2	10	11.91900	0.06	129.19469	0.003390
14	2	11	11.91900	0.06	129.19469	0.003390
15	2	12	11.91900	0.48	129.19469	0.003390
16	2	13	11.91900	0.48	134.79301	0.003388
17	2	14	11.91900	0.48	129.19469	0.003390
18	2	15	11.91900	0.24	22.59532	0.000001
19	3	16	11.91900	1.02	1.60259	0.000004
20	4	17	11.91900	0.48	1.60259	0.000004
21	5	18	11.91900	0.24	1.60259	0.000004

APPENDIX D. MODIFIED DATA FOR THE IEEE-RTS WITH RING BUS AND WITH MIXED STATION CONFIGURATIONS

Modified data for the IEEE-RTS with ring bus schemes

Tables D.1 and D.2 present the modified data for transmission lines, transformers and equivalent load circuits without and with station related maintenance outages for the IEEE-RTS with ring bus schemes respectively.

Table D.1: Modified transmission line and transformer data for IEEE-RTS with ring bus stations (without station maintenance outages)

Line No.	λ(f/yr)	r (hr)	U
Line 1	0.241513	16.14766	0.000445
Line 2	0.511520	10.09010	0.000589
Line 3	0.331100	10.13157	0.000383
Line 4	0.391100	10.12274	0.000452
Line 5	0.481100	10.10451	0.000555
Line 6	0.381831	10.09963	0.000440
Line 7	0.047763	332.34487	0.001812
Line 8	0.361723	10.12315	0.000418
Line 9	0.341411	10.13437	0.000395
Line 10	0.331567	34.97990	0.001333
Line 11	0.301160	10.15309	0.000349
Line 12	0.442234	10.08587	0.000519
Line 13	0.442390	10.08267	0.000509
Line 14	0.069354	233.70154	0.001850
Line 15	0.069354	233.70154	0.001850
Line 16	0.069354	233.70154	0.001850
Line 17	0.069354	233.70154	0.001850
Line 18	0.402843	11.08739	0.000510
Line 19	0.392410	11.09085	0.000497
Line 20	0.402885	11.08749	0.000510
Line 21	0.522843	11.05586	0.000660
Line 22	0.492885	11.07127	0.000623
Line 23	0.496022	8.79219	0.000498
Line 24	0.332446	11.11660	0.000422
Line 25	0.412885	11.07355	0.000522
Line 26	0.412885	11.07355	0.000522
Line 27	0.390004	10.93677	0.000487
Line 28	0.352885	11.09456	0.000447
Line 29	0.342843	11.08589	0.000434
Line 30	0.322885	11.09442	0.000409

Table D.1: (Continued)

Line No.	λ(f/yr)	r (hr)	U
Line 31	0.542885	11.05203	0.000685
Line 32	0.352885	11.09456	0.000447
Line 33	0.353324	11.08200	0.000447
Line 34	0.382843	11.09457	0.000485
Line 35	0.382843	11.09457	0.000485
Line 36	0.343324	11.07309	0.000434
Line 37	0.343763	11.06021	0.000434
Line 38	0.453324	11.05288	0.000572
Line 39	0.186068	156.84232	0.003331
Line 40	0.186068	156.84232	0.003331
Line 41	0.186380	156.58173	0.003331
Line 42	0.186068	156.84232	0.003331
Line 43	0.028068	19.39083	0.000062
Line 44	0.186068	156.84232	0.003331
Line 45	0.186068	156.84232	0.003331
Line 46	0.186380	156.58173	0.003331
Line 47	0.186068	156.84232	0.003331
Line 48	0.028068	19.39083	0.000062
Line 49	0.027763	19.59170	0.000062
Line 50	0.027353	19.80647	0.000062
Line 51	0.027353	19.80647	0.000062
Line 52	0.027353	19.80647	0.000062
Line 53	0.027689	19.61028	0.000062
Line 54	0.185601	157.23484	0.003331
Line 55	0.185601	157.23484	0.003331
Line 56	0.185538	157.28266	0.003331
Line 57	0.028071	19.38972	0.000062
Line 58	0.028224	19.28926	0.000072
Line 59	0.028224	19.28926	0.000072
Line 60	0.156743	132.50758	0.002371
Line 61	0.156304	132.87703	0.002371
Line 62	0.156743	132.50758	0.002371
Line 63	0.022882	13.40496	0.000035
Line 64	0.135140	3.10039	0.000048
Line 65	0.022443	13.64782	0.000035
Line 66	0.157182	132.14020	0.002371
Line 67	0.156743	132.50758	0.002371
Line 68	0.156743	132.50758	0.002371
Line 69	0.156743	132.50758	0.002371
Line 70	0.156304	132.87703	0.002371

Table D.1: (Continued)

Line No.	λ(f/yr)	r (hr)	U
Line 71	0.157182	132.14020	0.002371
Line 72	0.156743	132.50758	0.002371
Line 73	0.022443	13.64782	0.000035
Line 74	0.156743	132.50758	0.002371
Line 75	0.022443	13.64782	0.000035
Line 76	0.021961	13.90405	0.000035
Line 77	0.022882	13.40496	0.000035
Line 78	0.157182	132.14020	0.002371
Line 79	0.156743	132.50758	0.002371
Line 80	0.156304	132.87703	0.002371
Line 81	0.156743	132.50758	0.002371
Line 82	0.156743	132.50758	0.002371
Line 83	0.156304	132.87703	0.002371
Line 84	0.156743	132.50758	0.002371

Table D.2: Modified transmission line and transformer data for IEEE-RTS with ring bus stations (considering station maintenance outages)

Line No.	λ(f/yr)	r (hr)	U
Line 1	0.243501	16.28413	0.000453
Line 2	0.513508	10.17827	0.000597
Line 3	0.332547	10.27626	0.000390
Line 4	0.392547	10.24535	0.000459
Line 5	0.482547	10.20431	0.000562
Line 6	0.384228	10.20774	0.000448
Line 7	0.248758	121.62721	0.003454
Line 8	0.363986	10.23492	0.000425
Line 9	0.343267	10.26367	0.000402
Line 10	0.333626	34.95399	0.001341
Line 11	0.302674	10.31329	0.000356
Line 12	0.445176	10.16585	0.000526
Line 13	0.445536	10.15844	0.000517
Line 14	0.271103	112.85858	0.003493
Line 15	0.271103	112.85858	0.003493
Line 16	0.271103	112.85858	0.003493
Line 17	0.271103	112.85858	0.003493
Line 18	0.406470	11.17946	0.000519
Line 19	0.395479	11.19969	0.000506
Line 20	0.406564	11.17959	0.000519
Line 21	0.526470	11.12715	0.000669
Line 22	0.496564	11.14680	0.000632

Table D.2: (Continued)

Line No.	λ(f/yr)	r (hr)	U
Line 23	0.499700	8.88402	0.000507
Line 24	0.335567	11.24471	0.000431
Line 25	0.416564	11.16357	0.000531
Line 26	0.416564	11.16357	0.000531
Line 27	0.391285	10.99951	0.000491
Line 28	0.356564	11.19951	0.000456
Line 29	0.346470	11.19391	0.000443
Line 30	0.326564	11.20902	0.000418
Line 31	0.546564	11.12079	0.000694
Line 32	0.356564	11.19951	0.000456
Line 33	0.357561	11.17104	0.000456
Line 34	0.386470	11.19133	0.000494
Line 35	0.386470	11.19133	0.000494
Line 36	0.347561	11.16480	0.000443
Line 37	0.348558	11.13570	0.000443
Line 38	0.457561	11.12273	0.000581
Line 39	0.387470	112.42788	0.004973
Line 40	0.387470	112.42788	0.004973
Line 41	0.388190	112.22133	0.004973
Line 42	0.387470	112.42788	0.004973
Line 43	0.029470	19.59054	0.000066
Line 44	0.387470	112.42788	0.004973
Line 45	0.387470	112.42788	0.004973
Line 46	0.388190	112.22133	0.004973
Line 47	0.387470	112.42788	0.004973
Line 48	0.029470	19.59054	0.000066
Line 49	0.028758	20.05038	0.000066
Line 50	0.027807	20.56664	0.000065
Line 51	0.027807	20.56664	0.000065
Line 52	0.027807	20.56664	0.000065
Line 53	0.028616	20.07862	0.000066
Line 54	0.386391	112.73915	0.004973
Line 55	0.386391	112.73915	0.004973
Line 56	0.386262	112.77156	0.004973
Line 57	0.029473	19.58945	0.000066
Line 58	0.029830	19.36623	0.000075
Line 59	0.029830	19.36623	0.000075
Line 60	0.358582	98.17489	0.004019
Line 61	0.357585	98.44585	0.004019
Line 62	0.358582	98.17489	0.004019

Table D.2: (Continued)

Line No.	λ(f/yr)	r (hr)	U
Line 63	0.025279	13.70304	0.000040
Line 64	0.136421	3.35395	0.000052
Line 65	0.024282	14.22497	0.000039
Line 66	0.359579	97.90544	0.004019
Line 67	0.358582	98.17489	0.004019
Line 68	0.358582	98.17489	0.004019
Line 69	0.358582	98.17489	0.004019
Line 70	0.357585	98.44585	0.004019
Line 71	0.359579	97.90544	0.004019
Line 72	0.358582	98.17489	0.004019
Line 73	0.024282	14.22497	0.000039
Line 74	0.358582	98.17489	0.004019
Line 75	0.024282	14.22497	0.000039
Line 76	0.023191	14.80382	0.000039
Line 77	0.025279	13.70304	0.000040
Line 78	0.359579	97.90544	0.004019
Line 79	0.358582	98.17489	0.004019
Line 80	0.357585	98.44585	0.004019
Line 81	0.358582	98.17489	0.004019
Line 82	0.358582	98.17489	0.004019
Line 83	0.357585	98.44585	0.004019
Line 84	0.358582	98.17489	0.004019

Modified data for the IEEE-RTS with mixed ring bus and one and one half breaker schemes

Tables D.3 and D.4 present the modified data for transmission lines, transformers and equivalent load circuits without and with considering station related maintenance outages for the IEEE-RTS with mixed station schemes respectively.

Table D.3: Modified transmission line and transformer data for IEEE-RTS with mixed station schemes (without considering station maintenance outages)

Line No.	λ(f/yr)	r (hr)	U
Line 1	0.241513	16.14766	0.000445
Line 2	0.511520	10.09010	0.000540
Line 3	0.331100	10.13157	0.000383
Line 4	0.391100	10.12274	0.000452
Line 5	0.481100	10.10451	0.000555
Line 6	0.381831	10.09963	0.000391

Table D.3: (Continued)

Line No.	λ(f/yr)	r (hr)	U
Line 7	0.047763	332.34487	0.001763
Line 8	0.361723	10.12315	0.000418
Line 9	0.341411	10.13437	0.000346
Line 10	0.331567	34.97990	0.001275
Line 11	0.301160	10.15309	0.000300
Line 12	0.442234	10.08587	0.000469
Line 13	0.442390	10.08267	0.000411
Line 14	0.069354	233.70154	0.001850
Line 15	0.069354	233.70154	0.001850
Line 16	0.069354	233.70154	0.001801
Line 17	0.069354	233.70154	0.001801
Line 18	0.402843	11.08739	0.000492
Line 19	0.392410	11.09085	0.000497
Line 20	0.402885	11.08749	0.000473
Line 21	0.522843	11.05586	0.000660
Line 22	0.492885	11.07127	0.000605
Line 23	0.496022	8.79219	0.000498
Line 24	0.332446	11.11660	0.000404
Line 25	0.412885	11.07355	0.000504
Line 26	0.412885	11.07355	0.000504
Line 27	0.390004	10.93677	0.000469
Line 28	0.352885	11.09456	0.000447
Line 29	0.342843	11.08589	0.000434
Line 30	0.322885	11.09442	0.000391
Line 31	0.542885	11.05203	0.000685
Line 32	0.352885	11.09456	0.000429
Line 33	0.353324	11.08200	0.000429
Line 34	0.382843	11.09457	0.000485
Line 35	0.382843	11.09457	0.000485
Line 36	0.343324	11.07309	0.000434
Line 37	0.343763	11.06021	0.000434
Line 38	0.453324	11.05288	0.000572
Line 39	0.186068	156.84232	0.003331
Line 40	0.186068	156.84232	0.003331
Line 41	0.186380	156.58173	0.003331
Line 42	0.186068	156.84232	0.003331
Line 43	0.028068	19.39083	0.000062
Line 44	0.186068	156.84232	0.003331
Line 45	0.186068	156.84232	0.003331
Line 46	0.186380	156.58173	0.003331

Table D.3: (Continued)

Line No.	λ(f/yr)	r (hr)	U
Line 47	0.186068	156.84232	0.003331
Line 48	0.028068	19.39083	0.000062
Line 49	0.027763	19.59170	0.000013
Line 50	0.027353	19.80647	0.000062
Line 51	0.027353	19.80647	0.000062
Line 52	0.027353	19.80647	0.000062
Line 53	0.027689	19.61028	0.000062
Line 54	0.185601	157.23484	0.003331
Line 55	0.185601	157.23484	0.003331
Line 56	0.185538	157.28266	0.003331
Line 57	0.028071	19.38972	0.000013
Line 58	0.028224	19.28926	0.000072
Line 59	0.028224	19.28926	0.000013
Line 60	0.156743	132.50758	0.002353
Line 61	0.156304	132.87703	0.002366
Line 62	0.156743	132.50758	0.002353
Line 63	0.022882	13.40496	0.000017
Line 64	0.135140	3.10039	0.000048
Line 65	0.022443	13.64782	0.000017
Line 66	0.157182	132.14020	0.002369
Line 67	0.156743	132.50758	0.002353
Line 68	0.156743	132.50758	0.002353
Line 69	0.156743	132.50758	0.002369
Line 70	0.156304	132.87703	0.002353
Line 71	0.157182	132.14020	0.002366
Line 72	0.156743	132.50758	0.002371
Line 73	0.022443	13.64782	0.000035
Line 74	0.156743	132.50758	0.002366
Line 75	0.022443	13.64782	0.000017
Line 76	0.021961	13.90405	0.000035
Line 77	0.022882	13.40496	0.000035
Line 78	0.157182	132.14020	0.002371
Line 79	0.156743	132.50758	0.002371
Line 80	0.156304	132.87703	0.002371
Line 81	0.156743	132.50758	0.002371
Line 82	0.156743	132.50758	0.002371
Line 83	0.156304	132.87703	0.002371
Line 84	0.156743	132.50758	0.002371

Table D.4: Modified transmission line and transformer data for IEEE-RTS with mixed station schemes (considering station maintenance outages)

Line No.	λ(f/yr)	r (hr)	U
Line 1	0.243501	16.28413	0.000453
Line 2	0.513508	10.17827	0.000547
Line 3	0.332547	10.27626	0.000390
Line 4	0.392547	10.24535	0.000459
Line 5	0.482547	10.20431	0.000562
Line 6	0.384228	10.20774	0.000398
Line 7	0.248758	121.62721	0.003405
Line 8	0.363986	10.23492	0.000425
Line 9	0.343267	10.26367	0.000353
Line 10	0.333626	34.95399	0.001282
Line 11	0.302674	10.31329	0.000307
Line 12	0.445176	10.16585	0.000477
Line 13	0.445536	10.15844	0.000418
Line 14	0.271103	112.85858	0.003493
Line 15	0.271103	112.85858	0.003493
Line 16	0.271103	112.85858	0.003444
Line 17	0.271103	112.85858	0.003444
Line 18	0.406470	11.17946	0.000500
Line 19	0.395479	11.19969	0.000506
Line 20	0.406564	11.17959	0.000482
Line 21	0.526470	11.12715	0.000669
Line 22	0.496564	11.14680	0.000614
Line 23	0.499700	8.88402	0.000507
Line 24	0.335567	11.24471	0.000413
Line 25	0.416564	11.16357	0.000513
Line 26	0.416564	11.16357	0.000513
Line 27	0.391285	10.99951	0.000473
Line 28	0.356564	11.19951	0.000456
Line 29	0.346470	11.19391	0.000443
Line 30	0.326564	11.20902	0.000399
Line 31	0.546564	11.12079	0.000694
Line 32	0.356564	11.19951	0.000438
Line 33	0.357561	11.17104	0.000438
Line 34	0.386470	11.19133	0.000494
Line 35	0.386470	11.19133	0.000494
Line 36	0.347561	11.16480	0.000443
Line 37	0.348558	11.13570	0.000443
Line 38	0.457561	11.12273	0.000581
Line 39	0.387470	112.42788	0.004973
Line 40	0.387470	112.42788	0.004973

Table D.4: (Continued)

Line No.	λ(f/yr)	r (hr)	U
Line 41	0.388190	112.22133	0.004973
Line 42	0.387470	112.42788	0.004973
Line 43	0.029470	19.59054	0.000066
Line 44	0.387470	112.42788	0.004973
Line 45	0.387470	112.42788	0.004973
Line 46	0.388190	112.22133	0.004973
Line 47	0.387470	112.42788	0.004973
Line 48	0.029470	19.59054	0.000066
Line 49	0.028758	20.05038	0.000017
Line 50	0.027807	20.56664	0.000065
Line 51	0.027807	20.56664	0.000065
Line 52	0.027807	20.56664	0.000065
Line 53	0.028616	20.07862	0.000066
Line 54	0.386391	112.73915	0.004973
Line 55	0.386391	112.73915	0.004973
Line 56	0.386262	112.77156	0.004973
Line 57	0.029473	19.58945	0.000017
Line 58	0.029830	19.36623	0.000075
Line 59	0.029830	19.36623	0.000017
Line 60	0.358582	98.17489	0.004000
Line 61	0.357585	98.44585	0.004013
Line 62	0.358582	98.17489	0.004000
Line 63	0.025279	13.70304	0.000021
Line 64	0.136421	3.35395	0.000052
Line 65	0.024282	14.22497	0.000021
Line 66	0.359579	97.90544	0.004021
Line 67	0.358582	98.17489	0.004000
Line 68	0.358582	98.17489	0.004000
Line 69	0.358582	98.17489	0.004022
Line 70	0.357585	98.44585	0.004000
Line 71	0.359579	97.90544	0.004013
Line 72	0.358582	98.17489	0.004019
Line 73	0.024282	14.22497	0.000039
Line 74	0.358582	98.17489	0.004013
Line 75	0.024282	14.22497	0.000021
Line 76	0.023191	14.80382	0.000039
Line 77	0.025279	13.70304	0.000040
Line 78	0.359579	97.90544	0.004019
Line 79	0.358582	98.17489	0.004019

Table D.4: (Continued)

Line No.	λ(f/yr)	r (hr)	U
Line 80	0.357585	98.44585	0.004019
Line 81	0.358582	98.17489	0.004019
Line 82	0.358582	98.17489	0.004019
Line 83	0.357585	98.44585	0.004019
Line 84	0.358582	98.17489	0.004019

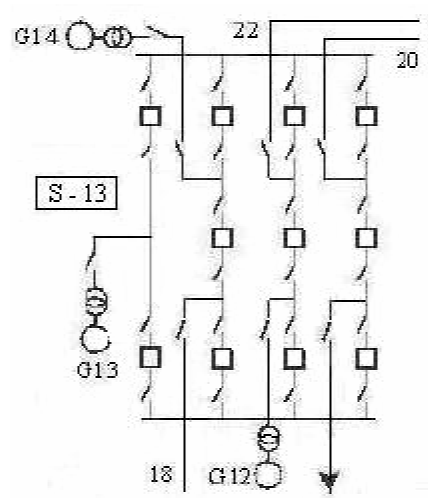

Figure D.1: Modified Station 13

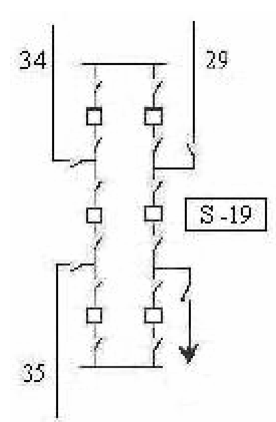

Figure D.2: Modified Station 19

APPENDIX E. RELIABILITY INDICES FOR SENSITIVITY ANALYSES OF GENERATING STATION 13 IN THE IEEE-RTS

Table E.1 shows the selected load point EENS as a function of the 138kV circuit breaker failure rates.

Table E.1: Selected load point EENS as a function of the 138kV circuit breaker failure rates (considering station maintenance outages)

Circuit breaker failure rate multiplier	1	10	20
Bus 35 (Ring)	70.816	611.443	1775.385
Bus 35 (Mixed)	18.373	542.841	1753.175
Bus 43 (Ring)	76.655	660.719	2057.414
Bus 43 (Mixed)	21.082	510.252	1780.910
Bus 45 (Ring)	109.460	667.096	2039.712
Bus 45 (Mixed)	41.754	642.699	1964.859

Tables E.2 and E.3 show that load point and system EENS as a function of the 230kV circuit breaker failure rates for the IEEE-RTS with ring bus schemes and with mixed station schemes respectively.

Table E.2: Load point and system EENS as a function of the 230kV circuit breaker failure rates for the IEEE-RTS with ring bus schemes

Station No.	Circuit breaker failure rate multiplier	1	10	20
9	Bus 44	718.873	746.569	820.327
10	Bus 45	109.460	109.626	111.177
13	Bus 49	124.765	1098.829	**3198.813**
14	Bus 50	175.650	873.615	2459.527
15	Bus 51	639.453	2540.159	7281.763
16	Bus 59	67.833	430.439	1222.079
18	Bus 61	145.437	1296.169	3944.767
19	Bus 62	1263.000	2125.009	3782.698
20	Bus 63	65.952	502.160	1554.964
	System	3752.043	10164.240	24819.060

Table E.3: Load point and system EENS as a function of the 230kV circuit breaker failure rates for the IEEE-RTS with mixed station schemes

Station No.	Circuit breaker failure rate multiplier	1	10	20
9	Bus 44	716.533	740.335	786.633
10	Bus 45	41.754	41.834	42.761
13	Bus 49	44.584	1075.068	**3237.062**
14	Bus 50	173.422	857.088	2387.930
15	Bus 51	568.037	1793.393	4311.035
16	Bus 59	72.370	440.323	1215.800
18	Bus 61	93.348	1176.547	3837.062
19	Bus 62	1241.966	2128.395	3840.043
20	Bus 63	71.711	517.567	1547.577
	System	3365.460	9112.317	21548.160

Load point and system EENS as a function of the 230kV circuit breaker failure rates at Station 13 for the IEEE-RTS with ring bus schemes and with mixed station schemes respectively are shown in Tables E.4 and E.5.

Table E.4: Load point and system EENS as a function of the 230kV circuit breaker failures rates at Station 13 for the IEEE-RTS with ring bus schemes

Station No.	Circuit breaker failure rate multiplier	1	10	20
9	Bus 44	718.873	727.931	748.701
10	Bus 45	109.460	109.553	109.673
13	Bus 49	124.765	1098.828	**3198.403**
14	Bus 50	175.650	177.866	183.121
15	Bus 51	639.453	647.870	667.225
16	Bus 59	67.833	68.453	69.940
18	Bus 61	145.437	146.029	147.123
19	Bus 62	1263.000	1277.009	1309.650
20	Bus 63	65.952	66.493	67.771
	System	3752.043	4761.681	6943.277

Table E.5: Load point and system EENS as a function of the 230kV circuit breaker failure rates at Station 13 for the IEEE-RTS with mixed station schemes

Station No.	Circuit breaker failure rate multiplier	1	10	20
9	Bus 44	716.533	719.329	726.000
10	Bus 45	41.754	41.757	41.822
13	Bus 49	44.584	1075.068	**3237.007**
14	Bus 50	173.422	173.990	175.462
15	Bus 51	568.037	570.394	576.220
16	Bus 59	72.370	72.487	72.911
18	Bus 61	93.348	93.417	93.812
19	Bus 62	1241.966	1246.277	1257.598
20	Bus 63	71.711	71.813	72.189
	System	3365.460	4406.269	6594.774

Modified configuration I for station 13

Tables E.6 shows that load point and system EENS as a function of the 230kV circuit breaker failure rates at Station 13 for modification I. Table E.7 shows that load point and system EENS as a function of the 230kV circuit breaker failure rates for modification I.

Table E.6: Load point and system EENS as a function of the 230kV circuit breaker failure rates at Station 13 for modification I

Station No.	Circuit breaker failure rate multiplier	1	10	20
9	Bus 44	718.807	724.885	738.902
10	Bus 45	109.460	109.475	109.567
13	Bus 49	115.856	1728.402	**5437.535**
14	Bus 50	175.647	176.922	180.418
15	Bus 51	639.423	644.781	657.673
16	Bus 59	67.833	68.151	69.165
18	Bus 61	145.437	145.622	146.392
19	Bus 62	1262.888	1272.177	1293.950
20	Bus 63	65.952	66.200	67.051
	System	3742.920	5378.233	9142.300

Table E.7: Load point and system EENS as a function of the 230kV circuit breaker failure rates for modification I

Station No.	Circuit breaker failure rate multiplier	1	10	20
9	Bus 44	718.807	743.498	809.933
10	Bus 45	109.460	109.548	111.071
13	Bus 49	115.856	1728.403	**5437.942**
14	Bus 50	175.647	872.671	2456.727
15	Bus 51	639.423	2537.071	7271.692
16	Bus 59	67.833	430.138	1221.280
18	Bus 61	145.437	1295.761	3944.031
19	Bus 62	1262.888	2120.176	3765.997
20	Bus 63	65.952	501.867	1554.233
	System	3742.920	10780.790	27015.820

Modified configuration II for station 13

Tables E.8 show that load point and system EENS as a function of all the 230kV circuit breaker failure rates for the IEEE-RTS with modified ring bus configurations II.

Table E.8: Load point and system EENS as a function of the 230kV circuit breaker failure rate for the IEEE-RTS with modified ring bus configurations II

Station No.	Circuit breaker failure rate multiplier	1	10	20
9	Bus 44	718.352	739.106	797.582
10	Bus 45	109.450	109.524	111.023
13	Bus 49	163.372	2307.492	**7677.071**
14	Bus 50	175.407	871.389	2453.369
15	Bus 51	638.808	2532.628	7259.535
16	Bus 59	67.736	429.750	1220.285
18	Bus 61	145.351	1295.501	3943.421
19	Bus 62	1262.265	2113.584	3747.499
20	Bus 63	65.869	501.561	1553.464
	System	3788.225	11342.200	29206.160

APPENDIX F. THE METHOD OF CALCULATING α AND β FOR THE WEIBULL DISTRIBUTION

The method to calculate the scale (α) and shape (β) parameters for Weibull distribution from the mean (μ) and standard deviation (σ) is refer to [40] and described in the following.

The expected value of the Weibull distribution is given by

$$\mu = \alpha\Gamma\left(\frac{1}{\beta}+1\right) \tag{F.1}$$

where Γ is the gamma function defined as

$$\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}\,dt \tag{F.2}$$

The standard deviation of the Weibull distribution is given by

$$\sigma^2 = \alpha^2\left[\Gamma\left(1+\frac{2}{\beta}\right) - \Gamma^2\left(\frac{1}{\beta}+1\right)\right] \tag{F.3}$$

The followed equation can be obtained by eliminating α from (F.1) and (F.3),

$$\frac{\Gamma\left(1+\frac{2}{\beta}\right)}{\Gamma^2\left(\frac{1}{\beta}+1\right)} = 1+\frac{\sigma^2}{\mu^2} \tag{F.4}$$

Using an approximate expression of the gamma function, (F.4) is approximated by

$$\frac{(1+\frac{2}{\beta})^{(0.5+2/\beta)}e^{-(1+2/\beta)}\left[1+1/12(1+\frac{2}{\beta})\right]}{\left[(1+\frac{1}{\beta})^{(1+2/\beta)}e^{-(2+2/\beta)}\left[1+1/12(1+\frac{1}{\beta})\right]^2\right]\sqrt{2\pi}} = 1+\frac{\sigma^2}{\mu^2} \tag{F.5}$$

Equation F.5 can be solved to obtain β using a bifurcation algorithm. The α is calculated from Equation F.3 using β.

APPENDIX G. RELIABILITY DATA COMPARISON FOR THE STATION COMPONENTS OBTAINED USING THE ACCURATE AND APPROXIMATE METHODS

Tables G.1 and G.2 show the reliability data for the bus bar obtained using the accurate and approximate methods when the slope factor *k* equals 5 and 10 respectively.

Table G.1: Reliability data for the bus bar for 1-year period (k=5)

Age of bus bar (yr)	failure rate (f/yr)	repair time (hr)	Unavailability (hr/yr) (accurate)	Unavailability (hr/yr) (approximate)	Unavailability
<30	0.025	10	0.024999	0.250000	0.000029
30	0.027083	20.307692	0.549965	0.550000	0.000063
31	0.031250	36.800000	1.149849	1.150000	0.000131
32	0.035417	49.411765	1.749650	1.750000	0.000200
33	0.039583	59.368421	2.349370	2.350000	0.000268
34	0.043750	67.428571	2.949007	2.950000	0.000337

Table G.2: Reliability data for the bus bar for 1-year period (accurate method, k=10)

Age of bus bar (yr)	failure rate (f/yr)	repair time (hr)	Unavailability (hr/yr) (accurate)	Unavailability (hr/yr) (approximate)	Unavailability
<30	0.025	10	0.249999	0.250000	0.000029
30	0.029167	29.142857	0.849918	0.850000	0.000097
31	0.037500	54.666667	2.049520	2.050000	0.000234
32	0.045833	70.909091	3.248795	3.250000	0.000371
33	0.054167	82.153846	4.447741	4.450000	0.000508
34	0.062500	90.400000	5.646358	5.650000	0.000645

Tables G.3 and G.4 respectively show the reliability data for the circuit breaker in the long term obtained using the accurate and approximate methods when *k* equals 5 and 10.

Table G.3: Reliability data for the circuit breaker in a long term (k=5)

Circuit breaker age (yr)	Equivalent active failure rate (f/yr)	Equivalent passive failure rate (f/yr)	Equivalent repair time (hr)	Unavailability (hr/yr) (accurate)	Unavailability (hr/yr) (approximate)
<10	0.00963	0.00107	93.62	1.011254	1.001734
10	0.012038	0.001338	103.696000	1.398748	1.386934
20	0.060188	0.006688	135.939200	9.141572	9.090934
30	0.108338	0.012038	139.521778	16.870718	16.794934
40	0.156488	0.017388	140.899692	24.586222	24.498934
50	0.204638	0.022738	141.629176	32.288122	32.202934

Table G.4: Reliability data for the circuit breaker in a long term (k=10)

Circuit breaker age (yr)	Equivalent active failure rate (f/yr)	Equivalent passive failure rate (f/yr)	Equivalent repair time (hr)	Unavailability (hr/yr) (accurate)	Unavailability (hr/yr) (approximate)
<10	0.00963	0.00107	93.62	1.011254	1.001734
10	0.014445	0.001605	110.413333	1.786215	1.772134
20	0.110745	0.012305	139.619130	17.256817	17.180134
30	0.207045	0.023005	141.656744	32.672860	32.588134
40	0.303345	0.033705	142.400635	48.034633	47.996134
50	0.399645	0.044405	142.786024	63.342422	63.304134